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Current Airframe Manufacturing Technologies in the Aeronautical Industry and Trends for Future Developments

Paulo António Gouveia Vieira

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Orientador: Prof. Doutor José Manuel Lourenço da Saúde

Co-orientador: Prof. Doutor José Miguel Almeida da Silva

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Para os meus pais Paula e José Vieira, e irmã Liliana.

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Resumo

A indústria aeronáutica está em constante mudança. O avião como produto tem vindo a evoluir, fazendo uso, na maioria das vezes, de novos e revolucionários materiais e processos de fabrico. Ao mesmo tempo, o mercado global está em rápida expansão com novos *players* a entrar no mercado tornando-o cada vez mais competitivo. Assim, é, portanto, importante analisar as opções que os fabricantes têm ao seu dispor para enfrentar este novo clima de competição e mudança na indústria.

Com isto em mente, este trabalho consistiu em fazer um levantamento das tecnologias de fabrico, com foco na maior secção da aeronave, a *airframe*, analisando de forma particular o uso de materiais compósitos e ligas leves e suas implicações ao nível do projecto, que posteriormente se reflectem na produção e operação de aeronaves. Posto isto, o estado actual e tendências de desenvolvimento futuro em termos de materiais, sustentabilidade ambiental, processos de fabrico, junção, métodos de reparação e inspecção, são avaliados, sempre do ponto de vista de projecto, prestando atenção às vantagens e desvantagens dos materiais compósitos e ligas leves, bem como aos obstáculos ao seu desenvolvimento e aplicação.

Aquando da análise às futuras tendências da aplicação de materiais, um estudo é apresentado para a quantificação dessas tendências para os materiais mais relevantes em termos de construção aeronáutica, tendo sido retiradas importantes conclusões em relação à mistura de materiais que irá compor as novas aeronaves nas décadas futuras, com base em tendências históricas obtidas de uma substancial colecção de dados.

Palavras-chave

Indústria Aeronáutica, Materiais Compósitos, Ligas Leves, Tecnologias de Fabrico, Tendências de Desenvolvimento, Produção de Aeronaves

Abstract

The aeronautical industry is an area in constant change. The aircraft as a product is evolving, making use, most of the times, of new revolutionary materials and manufacturing processes. At the same time, the global market is expanding quickly and new players are entering the market in increasing competition. At this point, it is, thus important to analyze the options that manufacturers have at their disposal to tackle with this new environment.

Having this in mind, this work aimed at assessing the current manufacturing technologies, focused on the biggest part of the aircraft, the airframe, analyzing in particular the application of composite materials and lightweight metal alloys and their implications in production and operations. In this scope, the current state and future trends of materials, environmental sustainability, processes, joining, repairing and inspection methods, are assessed, always from the point of view of the design, taking into account the advantages and disadvantages of composite materials and of the lightweight metal alloys, as well as the obstacles to their development and application.

When analyzing the future trends in material's application, a study is presented to quantify those trends for the most important materials in aircraft construction, from which conclusions were derived covering aspects related with the evolution of the mix of materials, in the years to come, in what aircraft construction is concerned, based on historical data from a substantial collection of aircraft data.

Keywords

Aeronautical Industry, Composite Materials, Lightweight Metal Alloys, Manufacturing Technologies, Trends of Development, Aircraft Production

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List of Acronyms

ACARE	Advisory Council for Aeronautics Research in Europe
ACPS	Airplane Creation Process Strategy
ASD	AeroSpace and Defense
ATL	Automated Tape Laying
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CIM	Computer Integrated Manufacturing
DFMA	Design For Manufacturing and Assembly
FAI	First Article Inspection
FML	Fiber-Metal Laminate
FPSP	Fine Particle Shot Peening
FRP	Fiber Reinforced Plastics
FRTM	Flexible Resin Transfer Molding
FSW	Friction Stir Welding
HTF	Hot Transfer Fluid
IATA	International Air Transport Association
IIASA	International Institute for Applied System Analysis
LCT	Liquid Crystal Thermoset
LSM2	Logistic Substitution Model 2
LST	Line Scanning Tomography
NASA	National Aeronautics and Space Association
NDI	Non-Destructive Inspection
OEM	Original Equipment Manufacturer

PE	Polyethylene
PEEK	Poliether Ether Ketone
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PPS	Polyphenylene Sulfide
RFI	Resin Film Infusion
RI	Resin Infusion
RIDFT	Resin Infusion between Double Flexible Tooling
RIFT	Resin Infusion under Double Flexible Tooling
RTM	Resin Transfer Molding
TRL	Technology Readiness Level
UK	United Kingdom
USA	United States of America
VARTM	Vacuum Assisted Resin Transfer Molding
VPS	Vacuum Plasma Spraying
WWI	World War I
WWII	World War II

1. Introduction

The aeronautical industry, which will be analyzed later in more detail, has been considered as one of the most technological advanced industries and an industry that is quite relevant in terms of employment and exports for any country. Nowadays, both the industry and the main product it produces, the aircraft, are very different in many ways from what they were 20 years ago. The aircraft is now more advanced, always making use of the most advanced systems and materials at the same time that the industry remains an example in terms of efficient production. Nevertheless, decisions at design stage are increasingly crucial as bad decisions can ruin an entire project. So, decisions must be made based on as much information as possible regarding the various aspects of design, production and operation.

1.1. Motivation

Currently, design teams have at their disposal many solutions in terms of materials and manufacturing processes, with each combination having a different impact on the final product. This work's objective is to provide not only the academic community but also stakeholders with an overview of the manufacturing technologies available to them in the case of airframe construction. Various aspects that influence decisions during design will be addressed, namely materials, manufacturing processes, environmental sustainability and joining, inspection and repairing methods, for the two most important types of materials in aeronautical construction, composite materials and lightweight metal alloys. The need for this arises from a gap in the existing literature, which is quite spread and most of the times too technical when referring to these issues.

On the contrary, the purpose of this work is an integration of these aspects from a design point of view, analyzing the implications that the two types of materials mentioned above have on downstream life cycle phases of the aircraft, namely production and operation. So, an assessment of the current manufacturing technologies related with composite materials and lightweight metal alloys will be made, looking at the referred aspects that influence decisions during design for each type of material.

However, aircraft are designed having into account technology developments that will occur in the short-medium term, as the design phase of an aircraft spans many years. With that said, the purpose of this work must also cover the short-medium term developments that are expected to occur in both types of materials covered.

Another gap identified in the literature has to do with the lack of information regarding the quantification of the diffusion/application of materials in aircraft construction. Many authors refer to the increase in the use of composite materials, but no quantification has been made, at least as far as the author is aware. So, and to complement the work on the future trends of development of composite materials and lightweight metal alloys, a quantification of the changes in the mix of materials in aircraft construction will be presented, with special attention to composite materials.

1.2. Dissertation Organization

Following the general description and goals, presented above, this work is divided in four chapters, including the current introduction with the motivation and organization of the dissertation.

In Chapter 2 a general history of the aeronautical industry is presented as to understand how aircraft construction has evolved from the beginning and so understand the main drivers of change throughout the decades.

Chapter 3, following the historic overview of the aeronautical industry, presents the current state of the industry.

Chapter 4, the main core of this work, is the state-of-the-art of airframe construction in terms of materials, manufacturing processes and joining, repairing and inspection methods for the two types of materials selected for this work, composite materials and lightweight metal alloys.

Chapter 5 explains how technology is implemented in the aeronautical industry.

Chapter 6 covers the trends for future development of the aircraft in general with special attention to the airframe, as is the main focus of this work. By the time airframe trends are explained, a study of the diffusion of materials in aircraft construction in the medium term is presented. In this study, the historical trends for the diffusion of the most important materials in aircraft construction is assessed and extrapolated towards the future following specific models for these cases.

In the end, Conclusions, Recommendations for future works, the Bibliography and the Annex with the data used for the study on materials’ diffusion are publicized.

2. Historic evolution of aircraft construction

In order to understand the current state of the aeronautical industry and consequently identify the trends for its future development, one must first look at its history and comprehend how changes occurred throughout history.

Mankind always dreamed of being able to fly, from the story of Icarus of the Greek mythology to the drawings of Leonardo da Vinci, history is full of visionaries that in some way or another contributed to keep the dream alive [1, 2]. With the XVIII century came the industrial revolution and the first flight of a manned aerial machine. Allegedly the first manned flight occurred in Lisbon when the Portuguese priest Bartolomeu de Gusmão flew in his balloon-like «Passarola» over the skies of the city [3]. However due to the lack of proof of this event the first manned flight is attributed to the French Montgolfier brothers in their hot air balloon in 1783 in Paris [1]. In these years, flight was seen more as an eccentricity rather than a proper mean of transport mostly due to the fact that it consisted only of balloons which are limited in speed and controllability. From this, in the next century important steps were taken towards the conventional propelled fixed wing airplane. For this the work of theorists in flight dynamics such as Sir George Cayley and James Walker were of great importance [1, 2, 4].

Also in these years, many experiments were made using vapor propelled airplanes and gliders with special attention to Otto Lilienthal, a German who between 1891 and 1896 made several flights on its gliders [1, 4]. This is considered to be one of the most important contributes to the success of the Wright brothers less than ten years later, providing important clues for the construction and control of the Flyer I. The Wright brothers ended up building a biplane with no fuselage and with struts and wire-braced structure in wood for the wings which were then covered in fabric. The Flyer I was propelled by a 12hp water-cooled Diesel engine made by the Wright brothers and flew for the first time in Kitty Hawk, North Carolina, USA in 17th of December of 1903 [1, 2, 4].

Interest in the new flying machine grew rapidly in Europe and the USA alike, in a way that new models appeared everywhere and in 1909 large scale production was started in France, thus marking the beginning of the aeronautical industry [4]. In these years, progress was made essentially in the way of continuous improvement of aircraft's performance following what can be assumed as a «higher, faster and farther» motto. The first airplanes consisted of biplanes built in wood and covered in fabric, making use of a wire-braced box-girder structure for the fuselage and wire-trussed strut supported wing with an internal spar-and-rib structure (Figure 2.1) [5]. The use of wood, such as spruce, as an aeronautical material has to do with the fact that wood was a material that was light enough to fly in low speed, and strong enough to withstand the forces of flight. Besides that, wood was easily available and had been used for centuries in many applications, meaning that a lot of knowledge existed in the processing and repairing of wood [5, 6, 7]. Fabric, mostly linen, was used essentially to cover the structure neglecting any structural functionality [6]. The biplane configuration allowed increased rigidity of the wing at the same time providing enough wing area to generate the required lift [8]. As for the fuselage structure, the use of the wire-braced box-girder structure in the early years, although costly and complex to build, was due to the fact that, as the airplane was still an experimental machine in many ways, several modifications and repairs were required and this type of structure made them easier to perform. Also, the lack of knowledge regarding the forces involved in flight made this type of structure a safer approach [9].

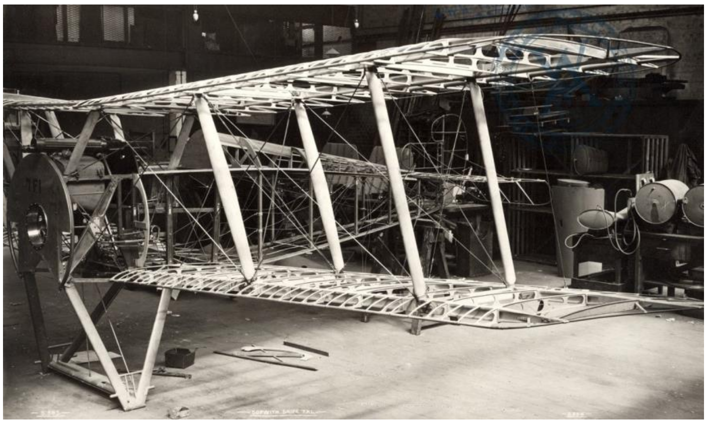


Figure 2.1 – Internal structure of Sopwith Snipe. Note the wire-braced box-girder structure of the fuselage and the wire-trussed strut supported wing with an internal spar-and-rib structure.

Source: The Vintage Aviator, http://thevintageaviator.co.nz/

As demand increased and aircraft performance advanced, the need to increase production and to increase structural resistance forced the simplification of the structure to make it easier to produce in a larger scale at the same time that the airplane was made stronger [6, 9]. A more streamlined shape was achieved although the same basic structure was kept. By 1912 a new type of structure appeared, the monocoque structure.

In this structure, it is the external surface that endures most of the stresses. Manufacturing a monocoque fuselage involves the production of two symmetric segments of the fuselage using molds, which were then glued together (Figure 2.2) [5]. This allowed very aerodynamic fuselages, but at a very high cost [9]. Various materials were used in these fuselages from plywood to mixtures of cork, paper and fabric [10]. In these early years of aviation manufacturing technologies were, however, limitative and monocoque structure did not succeeded due to the fact that it was very difficult to build and to guarantee its dimensional precision [5]. In turn, a mix of the two construction types mentioned above, monocoque and box-girder, gained much more importance. The result was the so called semimonocoque or stressed-skin structure which was stronger than the girder type but not as strong as the monocoque construction (Figure 2.3) [9]. In this type of construction the resistance to external stresses is made by the internal structure, using stiffners and bulkheads, and by the external surface by using a stronger material for the skin, i.e. wood [11]. With this type of construction a more streamlined and strong fuselage was possible without increasing manufacturing complexity too much [12].

It is now a good time to assess how airplanes were built in these years prior to WWI (1914-1918). As said earlier, large scale production of airplanes was a reality since 1909 and much has changed since the early days of aviation when airplanes were built by enthusiasts in their garages. Production, mainly manual, was undertaken in big rooms, in factories, destined to only one task, thus forming a chain in which components were produced, mounted, painted and tested until the final roll-out of the airplane. It is important to note that it was a very specialized job in the sense that most of the work was made by artisans who crafted wood in order to make the necessary components. This fact resulted in the increase of costs and time for production and in low standardization of components. This type of production remained basically the same until the metal transition, changing even more during the World War II (1939-1945) [2, 13].

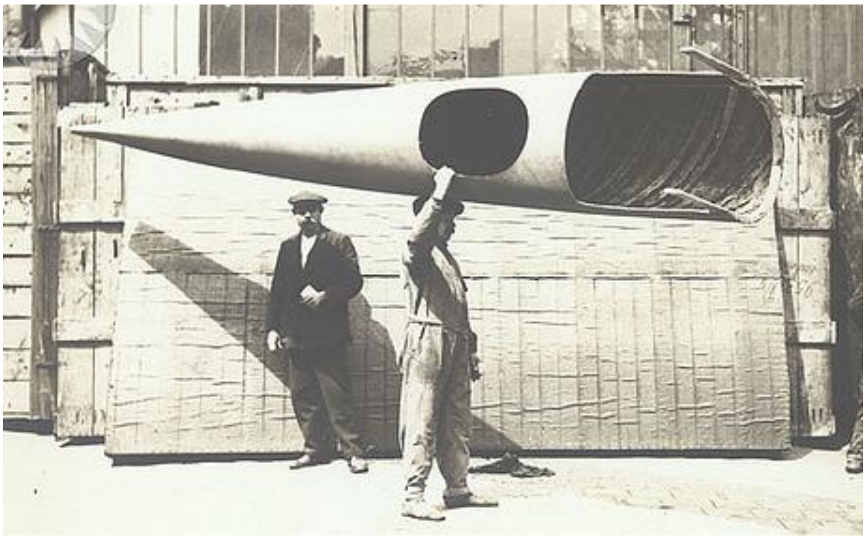


Figure 2.2 – Monocoque fuselage of a Deperdussin (1912).

Source: http://www.flickr.com/photos/publicresourceorg/494077728/in/photostream

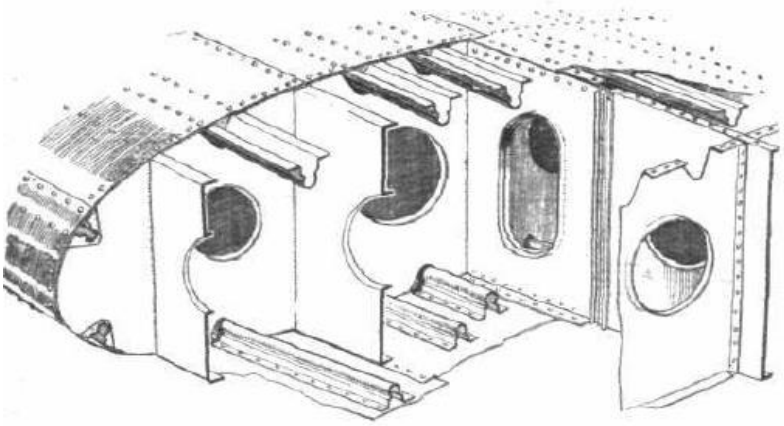


Figure 2.3 – Example of the stressed-skin concept in a wing structure [20].

Many times in Human history, wars act as a powerful driver of knowledge and World War I was no exception. Governments, acknowledging the importance of the aircraft, took control of the production hoping to better organize it. This led to an increased maturation of the industry especially in France, UK and Germany, in such a way that, by the time the USA entered the war, the American industry was quite far behind in terms of production expertise and knowledge [1, 14]

During the WWI, advances in the airframe were few, but very significant [4, 5]. The development of the cantilevered wing made the wings self-sustainable making the wires between the wings obsolete, as it improved the wing's strength. This development made the wings thicker, without diminishing wing efficiency, and made the monoplane configuration a more attractive possibility as the wing could better sustain the stresses during flight [5, 15]. It is important to note that the monoplane configuration was already employed, i.e. in the Antoinette (1909). In this case the wing was built up upon two transverse spars which were built on a lattice-girder principle [16]. This type of construction meant additional weight but lower drag. However, in the early years, as airplanes were slow, lower drag was not as an important factor as reduced weight was in terms of design.

Metal was also starting to be used in structural components as new lightweight alloys allowed its use [9]. Also during WWI a new method of forming the halves of fuselages permitted wooden monocoque fuselages with increased dimensional precision and more complex shapes [5]. By the end of the war the airplane was different and more evolved machine than in the beginning of the conflict. The semimonocoque structure succeeded in replacing the truss structure and the cantilevered wing allowed the use of the new and more powerful engines thus, increasing overall performance. Airplanes were now faster, heavier and stronger being capable of reaching 6000m of altitude and four-engine bombers were capable of carrying up to 3500kg of payload [4]. WWI also contributed to the increase of pilots, mechanics and engineers, thus creating the conditions to further expand the aeronautical industry [17].

With the end of the war and the sudden cancellation of orders by the military, many companies closed doors and those that stayed open struggled hard [18]. If we look at the events narrated above, we can see that right from the beginning the aircraft industry, as a large scale producer, depended mostly from military demand. The airplane was nothing more than a rich man's toy and a war machine. The industry therefore grew exponentially due to a sudden need arising from the war, being completely unsustainable in peace time. There was a need for new markets for the airplane. The answer was air transport. So, the need for new markets shifted the focus of aircraft development towards airplanes with the purpose of transporting goods and people [4].

Thus, begins the golden era of aviation which spanned from the 20's to the late 30's. During this period air transport grew rapidly with numerous cities being connected by regular flights [4]. For this new business to grow even more, airplanes needed further changes, and so air transport led to the period that became known as the structural revolution (or streamline revolution), which occurred during the 30's [4]. The structural revolution consisted mainly in the passage from wood to metal and from biplane to monoplane as the basic design for new airplanes. The monoplane design became attractive, as already said, by the use of the cantilevered wing combined with the stressed-skin concept. As for the transition from wood to metal the reasons are various and more complex.

The appearance of new steel and aluminum alloys, especially Duralumin, more resistant and lighter, made metal an even more attractive material than wood, for bigger airplanes [19]. These lighter and more resistant materials gave engineers the possibility of taking the stressed-skin and cantilevered wing concepts to a new level. The transition to metal was made step by step, in a way that structures began to be replaced by their metal equivalent. So the wooden structures of the wing, such as the spars and ribs, and of the fuselage were replaced by a variety of metal configurations [20].

In terms of manufacturing, metal is easier to process than wood and so, less skilled workers can be employed [5]. However, metal structures need different joining methods. Riveting seemed to be the best choice as it was simple, cheap, fast and could join different materials and because welding was sometimes impossible for some alloys and also not very reliable, easily producing poor results [19, 20, 21]. The major drawbacks of this technique are the extra weight and the fact that the component is drilled creating areas of accumulated tensions on the material. As it made assemblies easier, riveting also made it easier to disassemble components making maintenance easier. Nevertheless, welding began to be a very reliable process, from these years on, with the development of new welding procedures such as electric resistance welding and welding using atomic hydrogen [21, 22]. So, the years of 20 and 30 saw vast investigation being made in metal structures in aeronautics, mostly to understand the distribution of forces along the metal structures and to make the use of these structures as efficient as possible in terms of aerodynamics and weight saving [21].

Summarizing, the transition to metal can be seen as a natural step arising from developments in both structural concepts and materials. The all-metal airplane was thus born.

However important, these advances would mean little if they were not applied with success. That success came with the introduction of the first modern airliners such as the Boeing 247 (1933) and the Douglas DC-1 (1933) with retractable landing gear and improved cabin comfort, thus contributing for the increase in air transport in these years [23].

By the end of the 30's the world was at the brink of a new world war and once again the airplane was called to the battlefield. The result was an increase of aircraft production in all belligerent countries in order to ensure air supremacy [24]. To meet the increase in demand, changes were necessary at a production level. As seen, airplanes were built in batches by highly skilled workers using tools of general use. Also, workers would go from airplane to airplane performing tasks in a not very well organized way leading to errors [13]. The transition to metal allowed increased standardization and interchangeability of components, and the employment of less skilled workers. However, further changes were needed and so mass production was employed.

Mass production, already greatly employed in the automotive industry, had some difficulties in being applied to the aeronautical industry. The concept of assembly lines required a redesign of the entire factory, becoming longer and narrower to allow the movement of airplanes through the different stages of production (Figure 2.4). Organization of production was the key. Components to be assembled, tools (more specialized in contrast to the more general tools used before) and workers needed to be on the right place at the right time to perform the right task among the numerous tasks in which the airplane had been divided to facilitate organization. With improved standardization and interchangeability of components high levels of automation were achieved. All this made it easier and faster to produce airplanes and the result was a high production rate. This system was so successfully employed by the allies that some historians see it as one of the major contributions to their victory in WWII [13].

Again, war acted as a driving force of knowledge and many advances were made in the aeronautical sector, such as developments in communications and navigation but also, in materials with the use of plastics and the introduction of composite materials, although in short scale [25]. New manufacturing processes for metals, such as the electric furnace, made possible the synthesis of new lighter and stronger alloys, recent advances in welding made it possible to replace many riveted joints at the same time that polymeric resins, i.e. phenolytic resins, started being used as adhesives. Other developments to metals came in the form of coatings which protected them from corrosion, thermal effects and gave them increased strength [26]. However important these developments were, nothing is compared to the importance of the development of the new jet engine in a time when the internal combustion engine reached its peak of evolution in the aeronautical sector.

Figure 2.4 – Assembly line of the B-24. Note the rails to allow the movement of aircraft along the assembly line.

Source: http://www.vintagewings.ca/

The end of the war brought crisis again to the industry with many orders being cancelled, forcing many companies to merge in order to concentrate knowledge, minimize costs and maximize resources [18]. Air transport continued to grow even faster and the Cold War made governments pour money to research and to the development of new aircraft making use of the new jet engine, acknowledging the strategic importance of the airplane. This new engine permitted a huge increase in performance driving the development of new aircraft through a new phase of «faster, higher and farther» in both sides of the iron curtain. In air transport, airplanes were now developed to accommodate even more passengers providing also better comfort and taking them farther and faster [4].

The new engine also brought new challenges. The speed allowed by the jet engine induced thermal and pressure effects, which have to be accounted for during design. High speed air flow around the surface of the airplane cause it to increase friction and so a greater effect of temperature and abrasion. However, this effect is less serious than the fact that in high speed flight the sonic waves created collide with the wings. To solve these issues the wings became swept and new materials were applied.

The decades of the Cold War made the transition to the modern aircraft and aircraft production. Airplanes gained their «final» configuration as the most currently used materials and manufacturing processes saw their full potential explored and investigated throughout these years. In the case of materials a great attention was given to titanium, aluminum and, of course, composites [27]. Air transport required not only less costs of production but also of operation, and so investigation in lightweight materials became even more relevant resulting in the development of new metallic alloys and the appearance of new composite materials such as aramid, carbon and boron fibers and new resins [4].

The development of the computer marked another leap forward in aeronautical production as they allowed increased automation of manufacturing processes and the development of others, such as laser cutting, the design by computer and even a better internal organization of companies [28].

In spite of all these changes towards increased automation, the aeronautical industry remained until today as a very labor intensive industry with a quite big workforce if compared with other high-tech industries and if having in consideration that it has low production rates. This is due to the complexity and even personalization of airplanes, especially in the commercial sector, which combined to the low production rate and equipment costs make unpractical and risky to automate many of the tasks performed manually. So, most of the automation is in materials processing rather than in assembly [29]. One last important change in terms of aeronautical production occurred in the 90's with the implementation of Lean thinking due to the increased need to reduce costs. In this system, profit is seen as the sale value minus production costs and so emphasis is given to lower production costs by making it more efficient and by reducing waste. Lean production forced the entire company and suppliers to adapt rapidly to every order as the customer demands a certain product to be delivered at certain time and at a certain cost [30].

In conclusion, nowadays aeronautical production remains a craft industry with an efficiency-oriented mass production mentality in which design is now oriented by the motto «better, cheaper, cleaner and quicker» rather than «higher, faster and farther» [31]. In order to pursue these new goals, and as it will be presented in Chapter 4, for fiber reinforced plastics and lightweight metal alloys, materials and manufacturing processes are being pushed forward in their various domains such as properties improvement, sustainability and waste management in what materials is concerned, and such as increased automation, cost reduction, improved resulting products, component bonding and testing methods in terms of manufacturing processes.

3. State of the art of the aeronautical industry

3.1. Evolution of the industry over the past 30 years

As already seen in the previous chapter, the past 30 years changed the aeronautical industry significantly, shifting the attention of manufacturers towards the cost structure of the aircraft. For this, two major phases can be identified to justify this change in industry dynamics. The first was the American airline deregulation (1979). The airline deregulation broke the existing relationships between manufacturers and airlines, which prior to deregulation meant that a small number of airlines had mutually beneficial relationships with manufacturers in launching new products [32]. The new regulation was designed to provide better, cheaper services to the public by promoting competition in the airline business [33]. This forced the focus of new development of aircraft to shift from making the most technologically and functionally advanced aircraft to decreasing operating costs, increasing quality and consistency of performance for the aircraft and all its components [32]. With Airbus entering the market around these years, competition between manufacturers to reduce costs began to be extremely fierce [33].

The second phase was the end of the Cold War. Although its effects were greater in the military market, by the diminishing of defense budgets, the end of the Cold War made governments look for more affordable aircraft. So, as both sectors share virtually the same production base support, cost reduction became key and the industry in general began to focus heavily on Lean principles of manufacturing [32, 34].

3.2. Global industry

Following the mentioned phases, the industry reacted with a profound reorganization. The merging of companies, the growth of the base of suppliers, becoming one of the most complex networks of parts production and distribution known to any industry, and the cooperation between companies, forming joint ventures even between direct competitors, in some projects helped shape the industry we know today [35-37]. The result is a mainly bipolarized industry, in what commercial aviation is concerned, with two major OEM’s (Original Equipment Manufacturer) owning the market, Boeing and Airbus. These OEM’s are supplied by a variety of suppliers which in turn are supplied by other smaller suppliers forming a supply chain of N levels (tiers) of suppliers, which nowadays is a crucial part of the production cycle. Acknowledging that, OEM’s have been employing further collaboration and risk-sharing techniques with their suppliers [36, 37]. By sharing risk OEM’s also trust on their suppliers to further develop their components not only to reduce costs of production and of operation of the aircraft.

Commercial aircraft production is tied to air transport demand, both of passengers and cargo, which in turn is somewhat linked to potential economic growth. Air transport has been increasing steadily worldwide, specially the transport of passengers (Figure 3.1) which have been increasing at a rate of around 5% per year since 2002 [38].

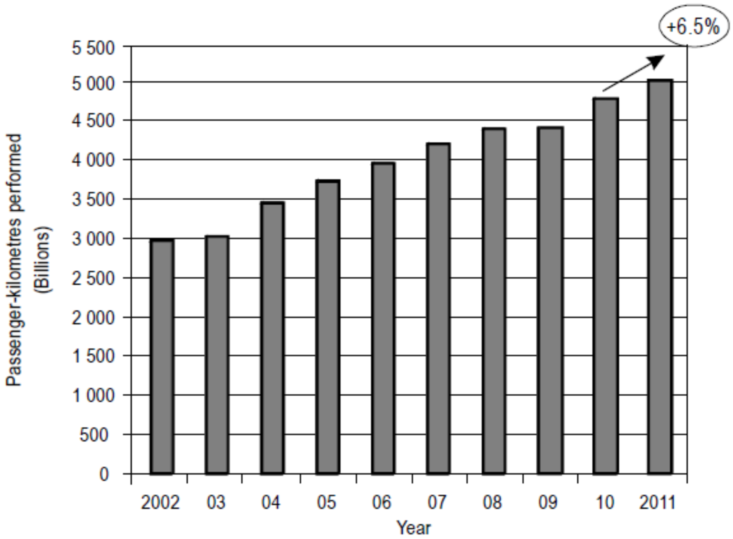


Figure 3.1 – Worldwide passenger-kilometers performed per year [39].

This increase in air transport demand, mostly in Asia and Middle East, has made airlines to put orders for new airplanes whether to directly meet demand or to replace old inefficient airplanes in order to diminish operating costs [40]. Nevertheless, it is possible to identify the periods when the global economy was growing and when it was shrinking just by looking at the orders chart (Figure 3.2). With orders increasing through the last few decades, production has been also steadily increased to record levels. Even with increased, production backlog keeps on increasing, reaching, for example, the astonishing number of 4682 aircraft for Airbus, the equivalent to 7 years of production [41]!

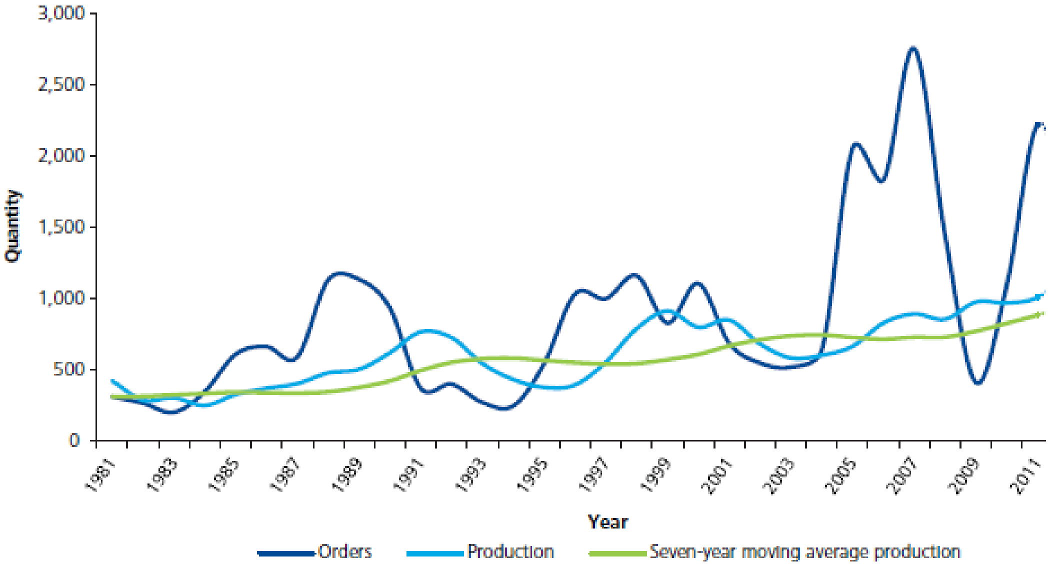


Figure 3.2 – Orders and Production of large commercial aircraft since 1981 [40].

The production shown in Figure 2 corresponds entirely to the production held in Europe and in the USA, the two market leaders to what aeronautical production is concerned. Although responsible for the biggest cut in what aerospace related revenue is concerned, the USA civil aeronautical production comes second to the European industry, on the latest figures published. While the USA generated around 40bn€ of revenue, the European civil industry generated, in 2011, around 70bn€. In terms of employment the European industry employs about 480000 people while the American industry provides job to 425000 people in the aeronautical sector. Overall, employment has been increasing in the European industry while it has remained quite stable in the USA over the past few years. In addition, production per employee has increased, mostly due to new manufacturing processes and improved production management. The majority of employees are involved directly in production, being the workforce composed essentially of highly skilled workers [42, 43].

3.3. Aircraft Production

As seen previously, aircraft production in the present is a very complex matter because it involves the production of many parts and components, using very advanced technologies, and because production is undertaken following strict aeronautical regulation and companies run on tight budgets and timescales. With globalization the big OEM's began spreading their influence and interests facing each other in a more opened world. Production, thus reached a world scale with suppliers from around the world being called to take more responsibility in the projects they participate. The complex network of suppliers, thus created, enables that, for example, parts produced in Asia are shipped to Europe or the USA for final assembly.

Nevertheless, these types of subcontracts tend to be diminished in periods of economic uncertainty so that more production is taken in-house [36]. Although civil aeronautical production is still a quite bipolarized sector the emergence of new economic powers, such as Russia and China, have brought forward a new set of players to the industry that promise to somehow challenge the established domain of Europe and the USA in this sector for the next years [44].

At the same time, globalization also means increased competition, and so costs have been the target of much attention. After a first phase of lean techniques being applied to production during the 90's, companies have now taken even further these cost reduction techniques to the entire company and forcing them to their suppliers. This way, waste has been reduced and supply chains have been optimized diminishing costs across all the productive cycle. In addition to this organizational cost competitiveness, OEM's have also and obviously thrived towards better aircraft. Since the 60's, airplanes have, more or less, kept their shape and the improvements made since then have been in order to improve their efficiency, comfort and performance. These design improvements result in operational savings for the airlines which nowadays look for the new and more efficient airplanes to replace the old ones, thus creating an important market for manufacturers.

Focusing now on the purpose of this work, the way airplanes are manufactured has also changed according to the more general changes already presented. So, manufacturing costs, included in production costs, have also been dealt with. Airplanes are extremely complex machines with a quite long manufacturing process. Whether manufacturing is undertaken by suppliers or exclusively by OEM's, components still have to meet requirements and regulations while companies struggle to deliver them faster and cheaper. This has been achieved through better management methods, reducing waste, and trough the implementation of more sophisticated manufacturing processes. As already referred on the previous chapter, processes have evolved in the way of increasing precision and quality, increasing automation and better usage of materials. However, manufacture has remained a quite manual job, especially for low production parts and in what assembly is concerned. Reasons for this have already been discussed on Chapter 2.

Of course manufacturing processes depend on the materials to be used in the airplanes, which in turn depend on other factors that will be addressed later. Since the metal transition in the 20's, metals have ruled the materials for airplanes. On the last 40-50 years, composite materials have appeared as possible choices for the engineers and their use have not ceased to increase since then. So, nowadays, in what the commercial airplanes is concerned, the airframe is a mixture of the application of metals and composites. Obviously in the case of metals, and talking about airplanes, what interests us are the lightweight metal alloys such as aluminum ones. Both these classes of materials will be discussed on the next section, being presented an extensive look at them in their various aspects, to provide an overview of the materials and processes used in the aeronautical industry and recent developments.

4. State of the art of materials and processes in the aeronautical industry

Having seen the evolution of the aeronautical industry since its origins and the current state of it, for the purpose of this work, and in order to understand the possible developments in aeronautical manufacturing processes and materials, one must take a look at the current state of these materials and respective manufacturing processes. Throughout the years, efforts have been made to reduce costs. For that, new materials and processes have been employed.

Nowadays, the most relevant types of materials in the aeronautical industry are composite materials and lightweight metal alloys. However, new materials and processes mean different or new challenges in their application. So, along this section, various aspects of the mentioned materials will be presented, as they are important for the decision of applying them in the aeronautical industry. Besides the obvious presentation of the materials themselves and the manufacturing processes associated with them, also an overview of the joining, repairing and inspecting methods will be presented. At the same time, and due to the increasing concern with environment, an overview of the recycling of these materials will be given. These are all aspects with great impact on the aeronautical industry and must be taken into account if one wants to analyze their future development and application in the industry.

The mentioned assessment will be first presented for composite materials, with focus on the so-called fiber reinforced plastics, and then for lightweight metal alloys, which in the case of the aeronautical industry are essentially aluminum, magnesium and titanium.

4.1. Composite materials

The most accepted definition for a composite material is a material with two or more distinct phases bonded with each other forming a material with different properties than the properties of its constitutes. On these phases different materials are generally used, with different properties and crystalline structure [45]. From this definition one can find a wide range of materials that can be assumed as composite materials, for example wood. However, for the purpose of this work we will be interested in the synthetic composites. Synthetic composites are composed of mainly two phases: matrix and reinforcement. The materials for these phases are produced in separate being brought together only during the manufacturing process.

From this we can already find an important advantage of composite materials, which is the possibility of optimizing the final material, enabling the production of a material with properties impossible for any other kind of material alone [45]. In general composite materials present low density, good resistance to fatigue, creep and corrosion, low thermal expansion coefficient and excellent mechanical behavior, especially to solicitations on the directions for which the material was optimized [45-47]. On the downside these types of materials are quite expensive, are fragile and are more susceptible to humidity and high temperatures [47].

4.1.1. Reinforcement phase

As said, composite materials are composed of essentially two phases: a matrix phase and a reinforcement phase. The reinforcement phase, as the name suggests, is responsible for sustaining the stresses that the composite material will be subject to [45, 47]. For the reinforcement we can have mainly three configurations: continuous fibers, discontinuous fibers and particles (Figure 4.1), and use metals, ceramics, polymers or elemental (i. e. carbon or boron) materials [45, 46]. For this work we will be interested only on ceramic, polymer and elemental fiber reinforcements as they are the most widely used in aeronautical industry.

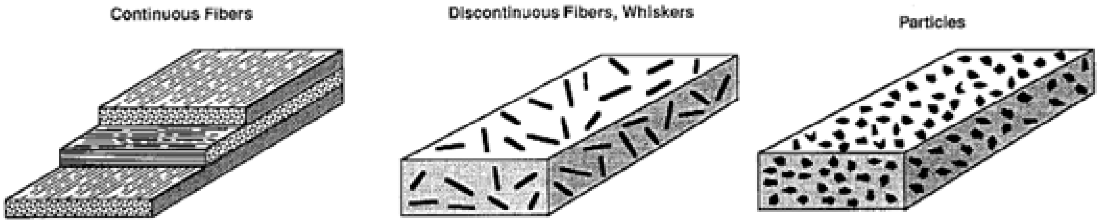


Figure 4.1 – Reinforcement configurations [45].

Fibers are filaments of material that are used due to the fact that materials in fibers allow better mechanical resistance than the same material in bulk and because they allow the already mentioned optimization of the composite material and consequently of the component [45]. For that, the fiber layers are oriented in a way that they can resist better to mechanical solicitations, with different layers being, in turn, oriented in different directions as they are stacked to form a laminate [47]. The three types of fiber orientation are: unidirectional, bidirectional and random [45].

As for the fiber itself, the most used are fiberglass, aramid (Kevlar) and carbon fibers although boron fibers are also relevant [45]. For their good mechanical behavior and low cost, comparatively with other fibers, fiberglass fibers are the most common [47]. These fibers, in general, have a lower modulus (≈80GPa), are more susceptible to creep and have low thermal and electrical conductivity [46]. On the opposite carbon fibers possess a combination of mechanical properties superior to the other fibers, having low density, being conductive and having an excellent resistance to fatigue, corrosion and creep, however, at high price [46, 47]. Another inconvenient of carbon fibers has to do with the fact that they are conductive and so, when in contact with aluminum induce in it galvanic corrosion [47]. Aramid fibers have an excellent damage tolerance, have low density and good mechanical properties but not to compression [47]. As for the boron fibers, the high performance fibers before the appearance of carbon fibers, they possess high modulus (≈400GPa) however, at a prohibitive cost being also very difficult to process [47].

4.1.2. Matrix phase

The matrix phase rather than resisting to the main stresses is responsible to transferring those loads to the fibers, maintain the fibers in the right place, provide some resistance to shear stresses and protect the fibers from abrasion [47]. We can have three types of materials for the matrix: metals, ceramics and polymers [45]. For the purpose of this work, only the polymer matrix composite materials will be addressed. So the work will focus on what is known as «fiber reinforced plastics» (FRP’s).

Polymeric matrices use synthetic materials made from chemical compounds whose structure is the repetition of smaller structures creating a macromolecule [48]. We thus obtain a viscoelastic material that adheres better to the fibers that reinforce it [46]. These materials when subjected to a process of heat exchange (a cure process) they acquire their final form being possible to make a distinction between thermosetting and thermoplastic matrices depending on the polymer to be used [46].

Thermosets are materials that when subjected to a cure process, acquire a final rigid form turning the polymer to a plastic with rigid tridimensional molecular bonds. After the cure process the material cannot be reheated in order to give a new shape, in other words it is an irreversible process in a way that during reheat the decomposition temperature is achieved before the fusion temperature of the material [46, 49]. In general these materials provide better mechanical properties than the thermoplastics. Furthermore, in terms of resisting to higher temperatures and to creep these materials surpass the thermoplastics being also possible to hand process them [49, 50]. However, these are materials that are very difficult to recycle, are more expensive, have a longer cure process, are harder to process and are fragile materials [49, 50]. Examples of thermosets are the epoxy resins, phenolic resins and polyimides [49, 50].

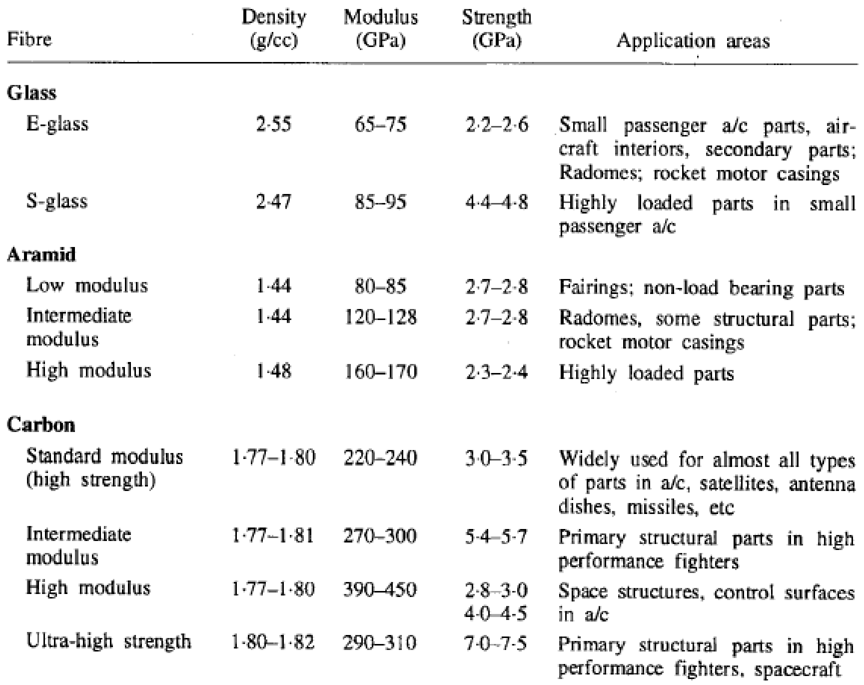
Thermoplastics are in many ways almost the opposite of thermosets. These materials when subjected to a cure process acquire a moldable plastic form, above the fusion temperature, after that they are cooled returning to the solid state below the vitreous transition temperature [50, 51]. This process can be repeated many times giving a new form to the component each time [46, 50]. In opposition to thermosets, thermoplastics are cheaper, have a good resistance to impact and to humidity, have improved toughness and are easier to repair, to recycle and to process [50, 52]. On the other hand, its ability to return to the plastic state when subjected to high temperatures makes the thermoplastics impossible to apply in certain cases where high temperatures are employed. Besides, thermoplastics have a worst tolerance to creep than thermosets [50]. Some of the more usual thermoplastics are the polyamides (Nylon), the polyether ether ketone (PEEK) and polyethylene (PE) [50, 51].

4.1.3. The use of composite materials in commercial aircraft

Composite materials are known to Man for a long time, however it was only in the early 30's that the so called modern composites appeared with the introduction of fiber glass [53]. The first applications in the aeronautical industry were essentially in secondary structures such as fairings, small doors and control surfaces [54]. After the 2nd World War the expansion of air traffic forced aeronautical companies to produce aircraft capable of transporting an increased number of passengers.

For that, weight had to be reduced in order to maximize useful payload. This demand conjugated with the appearance of new matrices and fibers increased the employment of composite materials in the commercial aviation, especially after the development of Boeing 707 in the 50's [54]. Ever since, composite materials have been replacing metal structures, and as of 2005 a reduction of 40% in the weight of secondary structures, by substituting light alloys, and a reduction of 20% in the weight of primary structures was predicted to be possible with the new generation of aircraft [55]. Nevertheless, the employment of composite materials in the aeronautical industry was slower than anticipated. This was mostly due to the high costs of certification and higher materials and production costs for composite components when compared to their metal equivalents [56].

Figure 4.2 provides a good idea of the application of the various composite materials in the present aeronautical industry. Polymer matrix reinforced with carbon fiber are the most widely used composite materials. In turn the most common materials for matrices are the phenolic and epoxy resins, polyesters and polyimides in the case of thermosets and PEEK and polyphenylene sulfide (PPS) in the case of thermoplastics [57].



Fibre	Density (g/cc)	Modulus (GPa)	Strength (GPa)	Application areas
Glass				
E-glass	2·55	65–75	2·2–2·6	Small passenger a/c parts, aircraft interiors, secondary parts; Radomes; rocket motor casings
S-glass	2·47	85–95	4·4–4·8	Highly loaded parts in small passenger a/c
Aramid				
Low modulus	1·44	80–85	2·7–2·8	Fairings; non-load bearing parts
Intermediate modulus	1·44	120–128	2·7–2·8	Radomes, some structural parts; rocket motor casings
High modulus	1·48	160–170	2·3–2·4	Highly loaded parts
Carbon				
Standard modulus (high strength)	1·77–1·80	220–240	3·0–3·5	Widely used for almost all types of parts in a/c, satellites, antenna dishes, missiles, etc
Intermediate modulus	1·77–1·81	270–300	5·4–5·7	Primary structural parts in high performance fighters
High modulus	1·77–1·80	390–450	2·8–3·0 4·0–4·5	Space structures, control surfaces in a/c
Ultra-high strength	1·80–1·82	290–310	7·0–7·5	Primary structural parts in high performance fighters, spacecraft

Figure 4.2 – Most used reinforcements in the aeronautical industry [57].

In the airframes of commercial aircraft the necessity to reduce weight has been promoting the increase in the use of composite materials in this sector. Large scale use of composite materials in the commercial sector was initiated by Airbus in the vertical tail of its A300. The «experience» was so successful that the use of composite materials was extended to other parts of the aircraft [54]. Essentially, in both the A3xx series of Airbus and in the later Boeing 7xx series tails, control surfaces, small doors, fairings and some fuselage beams are made in composite materials [58].

Over the years, with the maturation of composite materials' technology, the use of these materials have been pushed to new limits in a way that the next generation of commercial airplanes, the Airbus A350 and the Boeing 787, will possess around 50% of their weight in composite materials although, some doubts still exist mainly in what composite materials' long term durability is concerned. To note that, this increase in the use of composite materials in the commercial sector has to do with a multitude of factors, arising from the tendencies in the increasingly competitive aeronautical market. In general, these tendencies are based on cost reduction, aircraft's performance improvement, environmental impact reduction and on reduced time-to-market and customer, being the main focus, obviously, on the cost reduction during the entire life-cycle of the aircraft, from design to disposal [59].

4.1.4. State-of-the-art of composite materials

Let us now look at what are the most recent developments in the domain of composite materials. For that assessment a broad overview will be made covering different areas of composite materials, namely the advances in the manufacturing processes, the advances made in the materials themselves and the advances made in recycling, repairing and inspection of composite components.

4.1.4.1. Recent developments in composite materials

In the last decades substantial advances have been made in the field of composite materials. In what aeronautical industry is concerned, composite materials have been used essentially on secondary structures, however the advances in composite materials' technology have made possible the application of these materials on primary structures. Although thermosets have reined in the industry, thermoplastics have begun to be more attractive to aeronautical applications. An example is the use of thermoplastic resin reinforced with carbon fiber on the production of the J-nose of the Airbus A380 [60]. As for the thermosets, its development has not stopped. A new type of high performance thermoset, the liquid crystal thermoset (LCT), that combine the advantages of the thermosets and of thermoplastics, allow an easier processing, excellent thermal resistance, high mechanical resistance and excellent adherence between the resin and the fibers [61].

Instead of exploring the advantages of the composite materials, another line of investigation is to counter the disadvantages of these materials, hoping to make possible their application to other areas such as engines. So, investigation has been made to improve the resistance of composite materials to abrasion and thermal stresses. To do this, coatings are applied to the surface of composite components. The coatings, applied using sprays, are mostly composed of aluminum, tungsten, silica and zirconia. These coatings have already proved to be quite effective, enabling composites resistant to up to 800°C, existing some literature on the subject [62-67].

Other areas of the composite materials have been developed: nanocomposites, hybrid materials and biomaterials.

4.1.4.1.1. Nanocomposites

Nanomaterials consist in materials in which at least one of the dimensions is in the nano scale. In general these materials have a higher aspect ratio and therefore increased contact surface which allows improved physical and chemical interactions, and have better and different properties than materials in bigger scales [68, 69]. Hence, these materials allow the optimization, typical of composite materials, to be taken even further. It is then easy to understand that nanomaterials applied to composite materials have essentially a reinforcement purpose rather than the purpose of acting as matrix, due to the facts enunciated above. So, the inclusion of nanomaterials in both thermoplastics and thermosetting matrices has been proven to improve the performance of composite materials, as many authors describe [69-72]. Nevertheless, there are still aspects to be optimized such as the dispersion of the nanomaterials and their orientation in the matrix [72].

The materials to be used as reinforcement are various, although ceramics and carbon based materials are the most employed [68]. In what carbon based materials is concerned, graphene is noteworthy as it has the capability of conducting electricity, protect against electromagnetic interferences and because it has excellent thermal properties. This enables another advantage of nanocomposites that is the possibility of producing multifunctional materials [73, 74]. These multifunctional materials allow not only to have composite materials that can conduct electricity but also composite materials that can conduct heat and can act as acoustic damps and that can even possess optical properties depending on the materials used [75]. An example of a nanocomposite with optical properties is the ones produced using dioxide of zirconia which provides the nanocomposite with a high level of transparency at the same time that provides attractive mechanical properties [76].

Although promising, nanocomposites still need further investigation to validate them for industry applications. Another aspect that lacks understanding is the impact of nanocomposites on human’s health as nano scale particles can be hazardous [77].

4.1.4.1.2. Hybrid materials

Hybrid materials are materials that combine layers of composite with thin metal sheets alternatively (Figure 4.3), also known as fiber metal laminates (FML), with the purpose of taking advantage of both types of materials. They then possess the elasticity and durability of metals and the high resistance to fatigue of composites [77]. In order to bond both metal and composite a previous surface treatment is required so that the resin, that acts as adhesive, can hold both materials in a more efficient way [78]. As for the materials used, aluminum and fiberglass are the most used together, forming the hybrid material known as GLARE, although aramid fibers are also used with aluminum sheets to form ARALL. However, aramid or glass fibers can also be used together with titanium, on high temperature applications, and with magnesium. Magnesium based hybrid materials allow substantial weight reduction although the material produced is not as good as aluminum based hybrid materials in terms of, for example, corrosion resistance [79]. In terms of matrix both thermoplastics and thermosets are used [77]. Reference [77] also presents an excellent list of impact resistance studies for various FML.

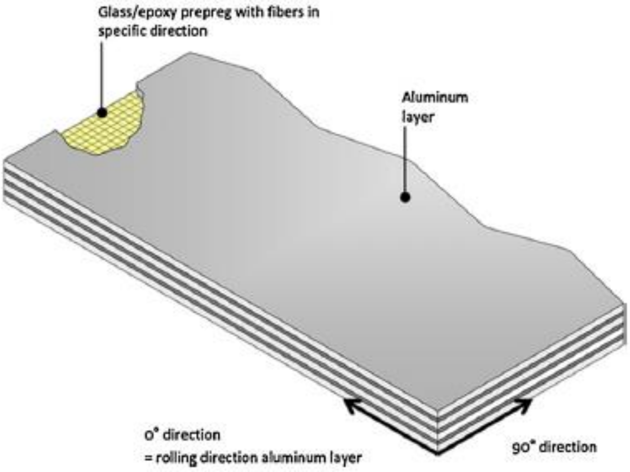


Figure 4.3 – Schematic of a hybrid material, in this case a GLARE laminate [78].

Despite being quite recent, these materials have already a substantial degree of application, especially in aeronautical components, possessing full certification for this industry. The most notable example of the application of hybrid materials in the aeronautical industry is the use of GLARE in many structural components, due to its impact resistance, of the Airbus A380, such as the leading edges of the tail and the top of the fuselage [80].

4.1.4.1.3. Biocomposite

With environmental concerns taking ever more importance in nowadays industries, a great investigation effort is being made also on the field of composites to replace some of the materials used in composite materials that are neither renewable in Nature nor biodegradable. Biomaterials, aside from being biodegradable and renewable in Nature they also have a low cost, low density, enabling its possible use on aeronautics, and have good specific mechanical properties [81, 82].

On biocomposites, although traditional matrices are used, a great effort has been made to replace them with biodegradable matrices such as the PLA, obtained from the sugar fermentation, the PHB, obtained from vegetal oils, and others obtained from soya and amid. These new biopolymers have been demonstrated to be capable of delivering interesting properties even if reinforced with natural fibers and compared to traditional matrices reinforced also with natural fibers [82]. Natural fibers, developed to replace the difficult to recycle and costly synthetic ones, can be based on almost anything from wood to pineapple leafs [81, 83]. Despite the many attempts with a wide variety of materials the most promising ones for natural fibers are wood, flax, sisal and hemp [84-86]. In terms of properties, natural fibers are still far from achieving those of traditional fibers such as glass and carbon. Nevertheless, their low density allows the use of these fibers on components with low mechanical stresses [84, 85]. Other disadvantages of the biocomposites in general are their low tenacity and their high susceptibility to environmental conditions that degrade these materials over time [82].

Another approach is to simulate what is found in nature. In this field of investigation materials found in nature are produced in labs to be used on composite materials. A material that has long been investigated with this purpose is silk, especially that of spiders. Spider's silk has a unique combination of tenacity, high resistance and low density, that if replicated could have enormous applications in many industries [87].

4.1.4.2. Manufacturing processes of composite materials

Manufacturing processes are the means to transform a certain raw material into a component to be used as it is or as a part of an assembly. The processing of composite materials can be a quite complex and time consuming process in the sense that a preparation of the material and a cure process are needed to accomplish a final component. Before looking at the processes in more detail a few considerations are important. The raw materials supplied to the industry come essentially in three forms: in pre-impregnated fibers (prepreg), in molding compounds and in rolls of weaved fibers with the resin in separate [88].

In the case of prepregs, fibers come with the correct amount of resin already mixed and partially cured. This enables a better use of the material avoiding waste, as the necessary resin for the material is already supplied, and enables products with better properties. From this we extract another consideration that is the fact that manufacturing processes for composite materials are less efficient than manufacturing processes for other materials, as manufacturing processes for composite materials still lack the maturity that manufacturing processes for other materials have [45]. So, nowadays manufacturing processes for composite materials are slow, laborious and costly, thus a great investment has been made in the automation of these processes not only to speed up processes but also to reduce manufacturing costs [45, 47].

Various processes exist, each one, in turn, with another great variety of variants depending on the manufacturer of the process equipment. However, only the general principles of the most used processes will be outlined here, being summarized in table 4.1.

Name	Advantages	Disadvantages	Description
Hand lay-up	- Allow more complex shapes - Simple tooling	- Labour intensive	Stacking of sheets of material with resin in molds.
ATL e Fiber Placement	- Automated process - Allow the manufacturing of biggers components	- Only allows less complex shapes - High cost - Time consuming - Complex	Automated lay-up of material by a moving machine on a moving mold.
Vaporization	- Low cost - Simple tooling - Can be automated	- Poor dimensional accuracy - Components with worst properties - Components are less replicable	Ejection of resin and chopped fibers simultaneously on a mold.
Filament Winding	- Can operate at a wide range of sizes	- Complex mandrel	Lay-up of fibers on a rotating mandrel to produce components in revolution.
Closed mold processes	- Production of single more complex components in one production cycle - Better surface finishing - Great dimensional accuracy	- High cost - Complex equipment	Production in heated molds that exert pressure on the component enabling at the same time the cure process.
Pultrusion	- Low material waste - Low cost - Increased automation	- Only produces constant section components - Fibers are always placed longitudinally	Fibers are pulled through a resin bath and two molds. The first aligns the fibers for the second that enables forming and cure.

Table 4.1 – Advantages, disadvantages and working principle of manufacturing processes for composite materials [45, 47, 89].

Hand lay-up is the oldest manufacturing process for composite materials and although it allows quite complex shapes it also requires skilled workers to efficiently produce a component using dry fibers plus resin or prepregs. In the case of ATL (Automated Tape Laying) a tape of prepreg is placed on a mold while in the process of fiber placement various strings of fibers converge to the machine's head, where the resin is applied, forming a tape that is then placed on the mold. The big difference in the application of both these processes is the fact that with fiber placement technique more complex shapes can be achieved than with ATL due to the physical impossibility of laying tapes of prepreg in considerable curved shapes. These processes are mostly used in aeronautics to produce large wing panels. In filament winding prepreg or fibers passing through a resin bath are placed on a rotating mandrel in order to produce composite revolution shapes such as cylinders for fuselages. The problem with this process arises from the fact that the mandrel inside the component must be removable. To solve this issue, mandrels can be disassembled or in some cases mandrels are inflated to produce the component and then deflated to remove the mandrel from inside the component.

Finally, pultrusion is essentially used to produce composite beams while closed mold processes consist mainly in the injection or infusion of resin into a two part mold that is closed with only the dry fibers or a preform inside. Preforms are three dimensional arranged fibers, which have been developed to closed mold processes, with the purpose of providing components through thickness resistance by weaving or braiding fibers using specific processes based on traditional seaming. Closed mold processes are used to produce complex unique parts with high quality in terms of properties and surface finishing. These processes have been investigated extensively in the recent years as they have a lot of advantages which will be highlighted during this chapter [45, 47, 89]. The processes presented are destined to thermosetting composites. Nevertheless, the processes for thermoplastic composites are essentially adapted from the processes for thermosetting composites and even some processes adapted from metals such as rolling and casting [56].

4.1.4.2.1. Curing process

Before having a final component it has first to go through a process to cure the resin in order to «lock» the fibers in their place and to give the final desirable properties to the material and component. The curing process consists in the transition of the resin from a plastic/liquid state to a solid state by heating and pressurizing the component during a certain period of time [45]. So, the quality and properties of the final product depend on time, heat and pressure applied to it during the cure process. With exception of the closed mold processes and pultrusion, referred to as out-of-autoclave processes, curing process can be made either by autoclave or in ovens [88]. However, the cure process can also be made at room temperature. The difference between an oven and the autoclave is that in an autoclave besides controlling temperature, it is also possible to control pressure. This enables the production of components of higher quality.

Pressure is, thus, a very important parameter in the sense that a composite laminate under pressure will have less inner defects as the bonding between fibers and resin will be made more efficiently [48]. With this in mind a vacuum bag is used to help compact the composite laminate during the cure process. Basically the composite laminate is covered with a bag to prevent any air escape while the laminate is surrounded with dams to prevent the resin from flowing away (Figure 4.4). After that, vacuum is applied to the interior of the bag exerting pressure throughout the entire laminate [48]. Further pressure during curing process can only be applied via autoclave.

As for the curing process in closed mold processes, it is done by heating the mold itself at the same time that pressure is applied by both parts of the mold, hence enabling components with as much quality as the ones obtained with autoclave or even better without the use of this enormous and costly equipment [48]. We then start to understand why out-of-autoclave processes are being investigated with so enthusiasm.

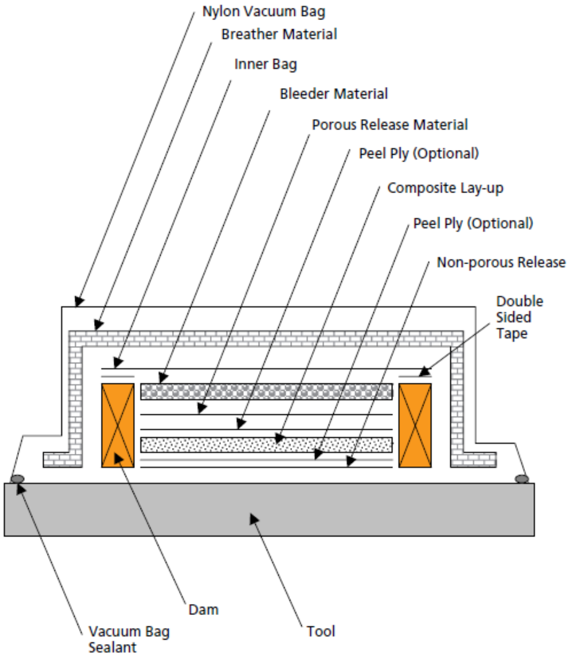


Figure 4.4 – Schematic of a vacuum bag [48].

4.1.4.2.2. Recent developments

Autoclave has been the standard in the industry to cure composite materials, however, the cost of such equipment, in terms of energy and time, and also the need to use a vacuum bag, that if punctured by accident during the curing process ruins the component, has forced manufacturers of around the world to search for new alternatives to the autoclave. Here come into play the, already mentioned, out-of-autoclave processes. These processes, in which, as the name suggests, the curing process occur outside an autoclave, are based essentially in the infusion of resin (RI) [90]. Among the resin infusion processes one can highlight RTM (Resin Transfer Molding) and RFI (Resin Film Infusion) as the two most popular processes in the industry in such a way that, for example, RTM is the main process in the production of composite components for the F-22 [91]. In this process, fibers are placed inside the mold that is then closed. Resin is afterwards injected inside the mold at high pressure while the mold is heated. All this promotes the adherence of the resin to the fibers and the curing process.

In contrast, RFI does need an autoclave. In this process a layer of resin is placed inside a vacuum bag together with the fibers. The set is then placed in an oven or autoclave subjected to pressure and heat that will bring together resin and fibers [91]. A variant of the RTM process is the VARTM (Vacuum Assisted RTM). The VARTM process makes use of vacuum pump that will create a vacuum inside the mold thus pulling the resin into the mold, in a similar way as vacuum cleaners operate [92].

All these processes allow a better use of materials and promote a better adherence of the resin to the fibers thus enabling the production of high quality components [90]. Although some of these processes are very costly to acquire, in general, they are in fact cheaper to operate as some studies suggest [93]. On this recent study, a comparison between prepregs and RI processes cured in autoclave, thermally and with microwave was made. The results show that the same component produced by a process of RI and cured in an oven is more environmentally friendly and allowed a global cost reduction of around 15% than a component produced using prepreg and autoclave cure. A similar study had already demonstrated the competitiveness of applying the process of RFI in the production of aeronautical components, being obtained components with better quality and at lower costs than the same component produced by hand lay-up [94]. In what RI processes is concerned another type is worth mentioning, the ones using flexible tools, which are examples the RIFT (Resin Infusion under Flexible Tooling), RIDFT (Resin Infusion between Double Flexible Tooling) and FRTM (Flexible RTM). In this kind of processes flexible membranes are used for the forming of the components (Figure 4.5) [95, 96].

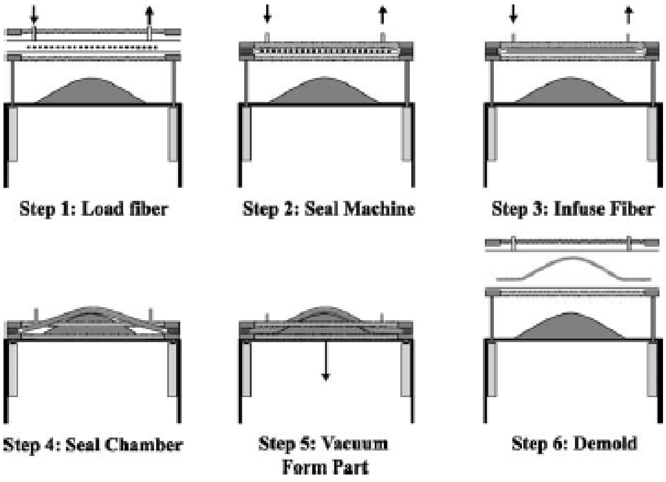


Figure 4.5 – Steps of RIDFT process [95].

A more recent process, that has even been demonstrated to be able to produce aeronautical components physically and chemically close to the ones produced in autoclave, has been developed. The process called Quickstep makes use of hot fluids to promote the curing of components. The laminate part is assembled on a single-sided tool using conventional lay-up, sealed in a vacuum bag and processed in a pressure chamber containing the glycol based HTF. The tool and laminate are supported between two flexible membranes in the pressure chamber (Figure 4.6). Temperature control is maintained by circulating the HTF through the pressure chamber, enabling rapid heating/cooling rates and precise control of the resin viscosity.

The big innovation in this process is the use of fluids rather than a gas (air) to cure the components, as fluids have higher heat capacity and higher thermal conductivity than gases. This fact enables increased control over temperature when compared to autoclave. Another advantage over autoclave, and other processes, is the possibility of curing only certain parts of the composite component leaving one section uncured that, as it will be explained later, can be used to bond different composite components. Lastly but not the least, with the Quickstep, curing cycles and operating costs can be as lower as 50% and 65% respectively when compared with autoclave [97, 98].

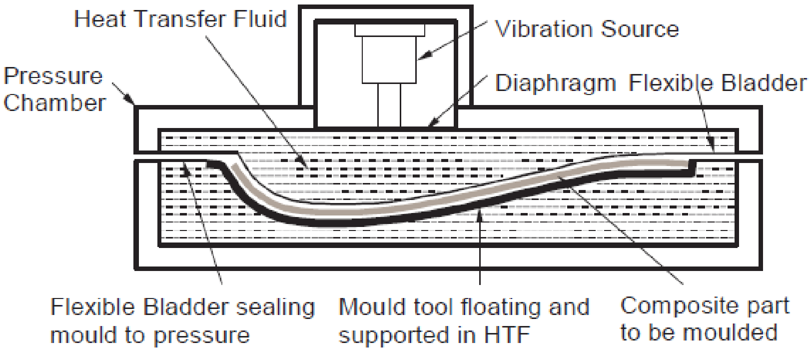


Figure 4.6 – Schematic of the Quickstep process [97].

4.1.4.3. Joining methods for composite materials

Joining composite materials with each other and with components made of other materials, namely metals, has been a huge concern for the aeronautical industry. Without being able to safely join components in composite one cannot make use of their advantageous properties. Nowadays joining composite materials can be made in two ways: mechanically and by means of adhesive bonding [99]. Mechanical joining consists in regular rivets or screws, for example, with the advantages of being able to be disassembled and of being simple to manufacture and inspect [100]. However, this type of joining requires the previous drill of the component originating areas of accumulated stresses in the vicinity of the holes created, further weakening the component and increasing its weight. So, increased attention is given to adhesives, especially those of polymer nature as a better bonding between adhesive and composite also depends on the compatibility of the material that the adhesive is composed of and the material that it will be attached to, in the most common case the polymer matrix of the composite. Besides that, adhesives work similarly to composite materials in the way they also need some sort of curing process in order to achieve their final bonding strength [99]. As composites, these adhesives are also resistant to fatigue, seal the junction for corrosion and allow a more stiff connection. At the same time, these adhesives cannot be disassembled, they are more difficult to inspect and are more prone to environmental degradation [56].

The main lines of investigation in joining methods for composite materials are towards replacing mechanical joining and essentially improving adhesives. In what adhesives is concerned epoxy ones are among the most widely used and developed as epoxy resins are also widely used in composite materials [100].

Following the development of the Quickstep process, another type of joining composite materials is the joining by melding. As mentioned above it is possible to cure only a section of the component leaving the rest uncured. That uncured part can then be joined with other component making use of the fluid resin of the matrix to efficiently join both components that are afterwards cured together (Figure 4.7) [98]. Studies have shown that once successfully achieved, the joining of the components by melding result in a negligible loss of mechanical properties when compared to monolithic components [101].

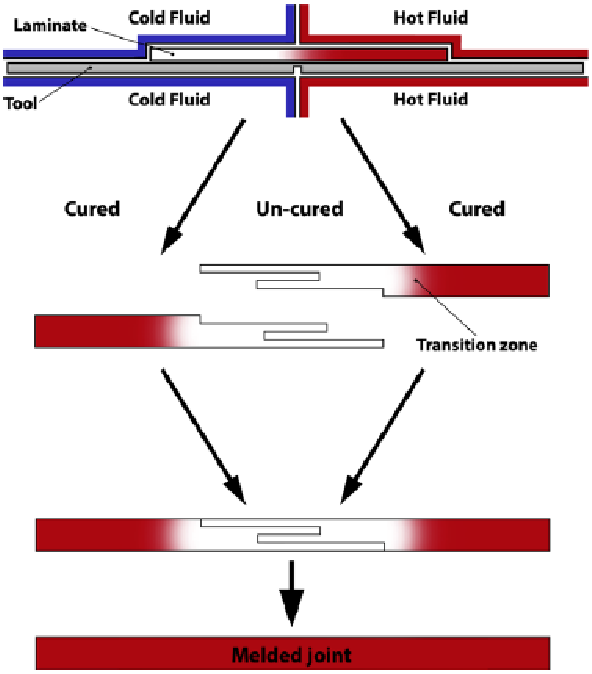


Figure 4.7 – Joining by melding [98].

With the development of thermoplastics, to a state where they start to compete with some thermosets, there have also been developments in the joining of these types of materials. Taking advantage of the fact that these materials can be heated, shaped, reheated and reshaped, welding is possible. The most used are electromagnetic welding (by radio frequency and induction), thermal welding (by laser) and welding by friction (via ultrasounds or vibrations), existing vast literature on the subject [102, 103]. Still in the field of thermoplastics, breakthroughs have been made with the purpose of creating hybrid materials by joining thermoplastics with metals. For that, a simple process called friction spot joining has been employed with promising results. In this process metal and the polymer matrix are joined by friction originated by a small rotating rod that will melt both metal and polymer which will then mix and bond when cooled [104].

4.2.4.4. Environmental sustainability of composite materials

Another great inconvenient of the composite materials is their end of life disposal. As already seen, this problem is somehow less relevant for thermoplastics as they can be reutilized just by reheating them and reshaping them. However, for thermosets the problem is a serious one. Nowadays there is not a proper industry of recycling thermosetting composite materials. However, due to the growing concern with the environment, the European Commission has issued directives to promote the recycling of these materials [105]. On the aeronautical industry manufacturers have formed joint ventures to address this issue, vowing to increase the percentage of aircraft weight that is recyclable [106].

The existing technologies for the waste management of composite materials, in general, can be divided in three categories: mechanical, chemical and thermal. Mechanical disposal consists in chopping the material to tiny bits, easier to manage and that can then be used in other applications such as construction works. This method does not allow the recovery of neither the fibers nor the matrix. On the contrary, with thermal and chemical disposal it is possible to recover, to a certain extent, both or at least one of the phases of the composite material. With thermal recycling waste is processed with the purpose of generating energy via incineration, is processed to obtain the fibers and generate energy from the resins using the fluidized-bed combustion recycling process or is processed in order to obtain both the fibers and the resin’s chemical compounds through pyrolysis. Another way of obtaining both fibers and matrix compounds is through chemical recycling using solvolysis processes [105-107].

Despite all the research being made and the political incentives towards recycling, as said there is not a recycling industry for composite materials. The reason is simple, the costs of the processes above described are still far from being economically viable and the recycled materials are still quite inferior to their original form [107]. Recent studies demonstrate that the loss in mechanical properties of recycled composite materials can be as high as 40% compared to the original material [108]. Nevertheless a different approach is being considered and applied. Just because materials loose properties that make them useless to apply in the aeronautical industry, it does not mean that those materials cannot be applied to other industries. So, a lot of effort has been made in order to validate and valorize these recycled composite materials for other industries (Figure 4.8). An example of this effort can be found, for recycled carbon fibers, in [105] while in [109] interesting results were obtained with the inclusion of recycled fiberglass particles in cement for construction.

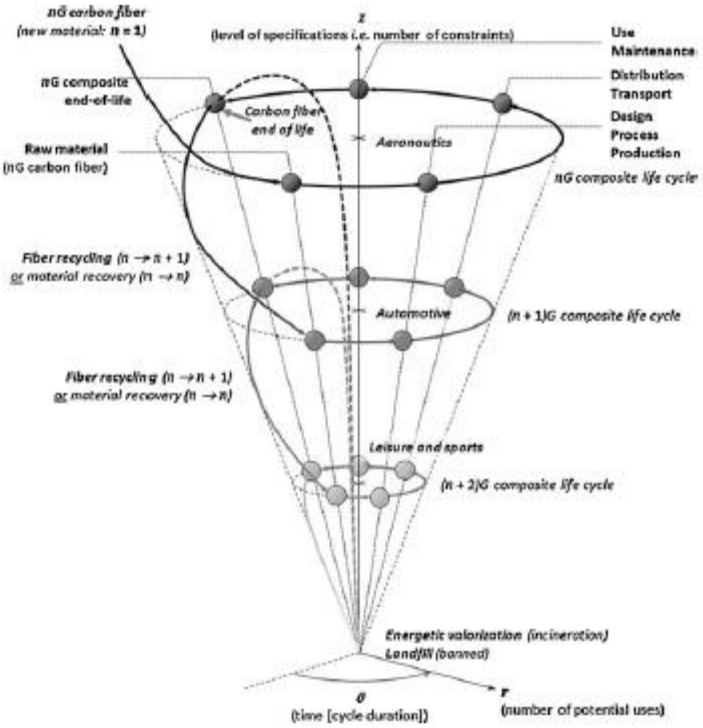


Figure 4.8 – Reuse of recycled composite materials in different industries [105].

4.1.4.5. Repair of composite materials

During an aircraft's life cycle repairs are inevitable. The conventional repairing of composite materials consists in the application of patches for bigger damages and the injection of resin for small damages [110]. Patches can either be bolted or bonded to the component. The advantages and disadvantages of each process have already been discussed on the section dedicated to joining. Nevertheless, the use of bolted patches will increase component's thickness and weight. On the contrary, the use of bonded patches does not increase component's thickness or weight but will require extra care on the preparation of the surface to receive the adhesive. In addition, the cure process has to be taken, so, a vacuum bag is normally used to locally cure the patch to its place. Usually in repairs the damaged area is removed and replaced with a patch, however, in the case of minor damage the defects are filled with resin or by fusion in the case of thermoplastics [56, 110-112].

Using the infiltration of liquid resin into the damaged zone under vacuum, being afterwards cured (Figure 4.9), has been investigated to be used on bigger damage than the ordinary for this method. Nevertheless, this is a process dedicated for low energy damage but that has yet to be optimized because a substantial amount of mechanical properties are lost [113]. However, increased understanding of the failure mechanisms of composite materials and the development of new resins make this a promising method to repair composite components.

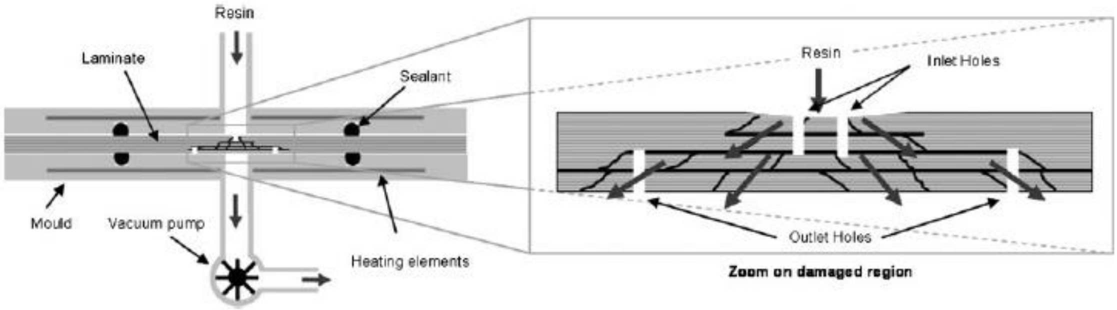


Figure 4.9 – Repairing by resin infiltration [113].

Another concept to repair composite materials is based on the previous transversal seam of the material using thermoplastic filaments before curing all together (Figure 4.10). When repair is needed all it takes is to heat the component, so that the thermoplastics, that have a lower fusion temperature than the composite's matrix, becomes plastic and flows to the flaws in the component. Once the gaps are filled with the thermoplastic material a curing process takes place. Although the properties of the component will not be equal to the initial ones, this method has been demonstrated to be repeatable several times before becoming useless [114, 115]. As seaming is done transversally it provides the composite laminate extra resistance to delamination improving general mechanical properties [57, 114-116]. To note that seam can be applied to both prepreg, dry fibers and also near net shape fibers [114, 116]. Another advantage of seaming is the further optimization it allows as with different thermoplastics and different seam patterns, different properties are given to the composite material [47].

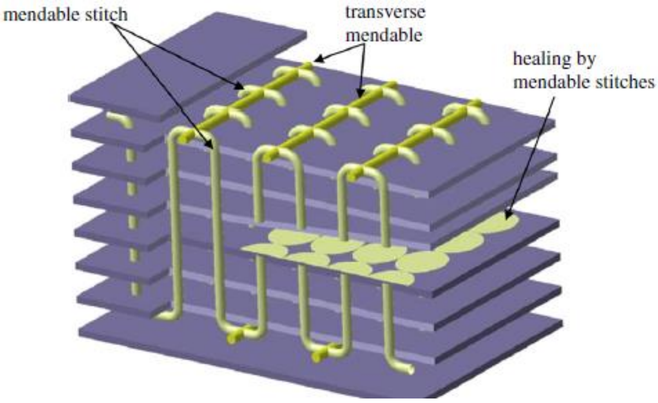


Figure 4.10 – Seaming of a composite laminate for posterior repair [114].

4.1.4.6. Non-Destructive Inspection of composite components

In order to allow the increase in the use of composite materials in the aeronautical industry one must be able to certify and validate the components making use of these materials. For that, the technological capability of inspecting those components for defects and flaws, after production or during the component's life cycle, is paramount.

The flaws or defects, in what composite materials is concerned, very often occur inside the material, being thus impossible to identify without breaking the component, so, non-destructive inspection methods are employed. The most common of these processes are X-rays, ultrasound methods (C-Scan and B-Scan), thermography, tomography, microwaves, acoustic emissions and optical methods.

Optical methods such as shearography, fotoelasticity, holography and the use of moiré patterns, detect variations on the materials based on parameters' variation linked to the reflectivity of the material [56, 57, 117, 118]. Shearography is perhaps the most widely spread inspection technology in the aeronautical industry as it is capable of efficiently and quickly identifying quite small damages on the surface of the components. This process uses a heat source in its analysis, being also developed the use of vibrational excitation for the analysis [119]. However, these types of processes, very often, require the parallel use of other inspection methods in order to better analyze the true dimension of the defects or flaws even towards the interior of the component [120, 121].

In the field of thermography, developments have been made to analyze bigger components by making the process faster and continuous, as the traditional thermography only allows the analysis of a section of the component at a time. Hence, a method called Line Scanning Thermography (LST), although not recent, has been a target for new developments made possible by the developments in computer aided image processing, allowing results similar to other processes such as C-Scan (ultrasound) [118].

Yet another emerging technique relies in the use of piezoelectric ultrasonic transducers that can be inserted permanently on a composite component to assess the state of the component by user request or automatically. Their basic principle is similar to ordinary ultrasounds with the particularity of using Lamb waves, as they describe elastic perturbations both in the parallel and perpendicular directions [117].

4.2. Lightweight metal alloys

A metal is a category of materials which include both metallic elements and their alloys, generally characterized by properties of ductility, malleability, luster, and high electrical and thermal conductivity [45]. Metals and their manufacturing processes have been developed since the ancient times. Even the first alloys were produced some millennia ago. Alloys are metals composed of two or more elements, in which at least one of those elements is a metal, and can be divided into two major categories: solid solution, in which a metal is dissolved into another to form an homogeneous mass of material (phase), and intermediate phases, in which the solubility limit of one element in another is reached and a second phase is formed [45].

From the first extraction of copper in around 8000 B. C. to the use of highly advanced alloys of nowadays, throughout history, metals have marked the progress of mankind. Nowadays, metals are still a crucial material in our society even though a wide variety of materials have been developed during the course of the years to replace them in many applications. The reason for this is the properties metals possess. Aside from those already presented, metals also possess, in general, great toughness and possess high stiffness and strength, properties in which metals surpass any other type of material. These properties allow metals to be chosen as the primary material for structural frameworks, and the aeronautical industry is no exception.

In the aeronautical industry, as seen Chapter 2, metals have been used since the beginning, although not structurally. These applications included the engine, obviously, but also the wires, to give some rigidity to the wings, among other small parts. The transition to full-metal airplanes during the 20's, due to the reasons already discussed on Chapter 2, allowed the airplane to go even further in its development. In general, this was only possible due to the advances on lightweight metals and alloys. Aluminum has since been the material of choice in what aircraft construction is concerned [47]. Nevertheless other lightweight metals have been developed and employed. Magnesium although it was quite used during the initial stages after the metal transition and during the World War II, its use then declined due to the serious drawbacks magnesium has. However, in recent years advances have been made in magnesium to overcome its disadvantages and turn it into a viable material for structural aeronautical applications. Another lightweight material is titanium. Titanium has become a very important material for the airframe due, essentially, to the possibility of replacing heavier steel alloys without jeopardizing structural integrity [47].

So, during this chapter and as done for composite materials, the use and recent developments in aluminum, magnesium and titanium alloys will be presented as they are the most widely used lightweight metal materials in the aeronautical industry. Being metals, they have quite similar aspects when it comes to manufacturing processes, joining, repairing and inspecting. However, differences exist and will be underlined here, as they change entirely the way these materials are picked and applied.

4.2.1. Aluminum

Of all major metals, aluminum is one of the most recent ones to be made available to the industry in general, being discovered and characterized only during the XIX century. In order to obtain aluminum a three step process is needed. First bauxite ore is extracted, washed and crushed, and then the Bayer process is applied in order to obtain alumina (Al_2O_3) by the precipitation resulting from the solution of the bauxite in aqueous caustic soda under pressure. After that, a process of electrolysis is applied to separate the elements of alumina thus producing aluminum [45].

Pure aluminum has very few applications. However, aluminum can be combined with other materials in order to produce alloys that allow a very wide range of properties' combinations. Common materials added to aluminum to form alloys include copper, magnesium, silicon, manganese, zinc and lithium [45]. These combinations allow a wide range of properties turning aluminum alloys into a very attractive material. The attractiveness of these alloys is that they are relatively cheap, light weight metals that can be heat treated to fairly high strength levels, resulting in materials with high strength-to-weight-ratio, and are one the more easily workable of the high performance materials, also resulting in lower costs [47, 122]. Furthermore, aluminum alloys are very resistant to corrosion, very conductive, easy to recycle, easy to join, do not brittle under low temperatures, actually becoming stronger as temperature drops, and are very ductile [45-47]. On the downside, aluminum alloys, have a low modulus of elasticity (≈69GPa), meaning that they can absorb more energy but at the same time deform more, have a quite low melting temperature (≈500°C), and can be susceptible to corrosion under stress [46, 47].

Three categories exist for alloys, wrought non-heat treatable alloys, wrought heat treatable alloys and casting alloys. Wrought alloys are produced mechanically, being wrought non-heat treatable alloys unable to be strengthened by precipitation hardening, only mechanically, while wrought heat treatable alloys can. Wrought heat treatable alloys, through precipitation hardening, can develop quite high strength levels, being the most used on aeronautical industry as will be shown [46, 47]. The process of precipitation hardening consists of heating the alloy to a temperature that is high enough to put the soluble alloying elements in the solution. After that the alloy is quenched to a lower temperature to keep alloying elements trapped in the solution. The alloying elements will then form a uniform distribution of very fine particles. This fine distribution of precipitates will harden and strengthen the alloy. As for casting alloys they are cast directly to the near-final finished shape, by melting the alloy and pouring it into a mold to form a part [46, 47].

4.2.2. Magnesium

Being the lightest of the structural metals, magnesium is obtained from sea water through a series of chemical reactions culminating in a final electrolysis process to isolate magnesium, which is then turned into ingots [45]. Since it is obtained from sea water, magnesium is seen as a virtual inexhaustible resource [46].

As a pure metal, magnesium lacks strength for most engineering applications. However, it can be alloyed with other elements and heat treated in order to achieve mechanical properties similar to some aluminum alloys [45]. In general magnesium alloys possess, low density, high specific strength, good weldability under controlled atmosphere, high damping capacity, good castability and is easily available [122, 123].

In contrast, the most significant problems of magnesium alloys are the low corrosion resistance, being a very chemically reactive element, the limited cold workability, creep resistance and high strength, and low elasticity modulus at the same time that it has a high degree of shrinkage on solidification [123]. Nevertheless corrosion resistance can be very high in high purity die casting alloys, at the same level of aluminum alloys, fact that has contributed for the expansion of the use of magnesium alloys [46]. So, we can then start to see that magnesium and aluminum are in direct competition in many applications. Aluminum alloys have increased maximum strength and higher modulus, while magnesium alloys are much lighter and, for some alloys, are more corrosion resistant [47].

Again, as aluminum alloys, magnesium alloys can be either wrought or cast and have similar treatments in order to increase their strength whether by heat treatment or by cold working. Cast magnesium alloys can produce acceptable strength values but at room temperature ductility remains fairly low and gas porosity originated during the casting process can difficult the application of heat treatments. As for wrought magnesium alloys, they are more suitable for high performance structural applications as they possess high ductility and strength [122].

Magnesium alloys, although having very interesting properties, still have a number of issues to be dealt with, namely in terms of workability and corrosion resistance. Nevertheless, a lot of development has been made to counter these advantages, as it will be presented later.

4.2.3. Titanium

Titanium is the third and final material that will be presented here as a lightweight material. It is obtained from rutile or ilmenite ores which are then converted to titanium tetrachloride ($TiCl_4$) by reacting with chlorine gas. After that a series of distillation processes are applied to remove impurities creating a highly concentrated titanium tetrachloride that is then reduced to metallic titanium, in an inert atmosphere, by reaction with magnesium or sodium which is known as the Kroll process [45].

Titanium alloys often use aluminum, copper, tin, vanadium and magnesium as alloying elements which provide titanium with very interesting properties [45]. Among them, is the high strength-to-weight ratio that allows titanium to replace steel in many high strength applications, the great fatigue resistance, better than aluminum, the excellent corrosion resistance, superior to aluminum and steel, the capability of operating at relatively high temperatures (until above 550°C), and the fact that it is compatible with composite materials [45, 47, 124]. As for the disadvantages, they mainly consist on the high price of both extraction, despite titanium being the fourth most abundant element in earth's crust, and processing [47]. The reasons for this are high melting point, extreme reactivity and the fact that the Kroll process used to produce titanium is very energy-intensive and does not allow a continuous production but instead a batch production [47, 125]. Just to quantify this disadvantage, titanium ingots are six times more expensive to produce than aluminum ones [124].

Titanium exists in two crystalline structures, being one stable at low temperatures and the other stable at high temperatures. At room temperature unalloyed titanium has a hexagonal close-packed crystal structure known as alpha phase and at high temperatures it is a body-centered cubic structure and is called beta phase [47, 124]. So, titanium alloys are classified according to the amount of alpha and beta retained in their structure at room temperature, being divided in alpha alloys, alpha plus beta alloys and beta alloys, which are stabilized, using alloying elements, to hold the beta structure at room temperature [47].

Alpha alloys generally have superior creep resistance to beta alloys, satisfactory strength, toughness and weldability but poorer forgeability, being more prone to forging defects. However, alpha alloys cannot be heat treated. Alpha plus beta alloys, which possess both crystalline structures at the same time, possess good formability and when properly treated have an excellent combination of strength and ductility. They are also stronger than alpha and beta alloys. Finally, beta alloys, have higher ductility, excellent formability, forgeability and hardenability, as they respond rapidly to heat treatments. Nevertheless, these alloys are more susceptible to creep at higher temperatures [46, 47, 124]. In the end properties of titanium alloys is a combination of alpha and beta phases, which in turn are dependent of the alloying elements added, in order to meet requirements.

4.2.4. Application of lightweight metal alloys in the aeronautical industry

As already mentioned, airframe manufacturers look for materials that can provide weight and cost reduction at the same time they allow improvement in mechanical properties. So, and as seen, lightweight metal alloys have a wide range of properties that make them very attractive to the aeronautical industry and they have been used since the metal transition in the 20's. Let us now then analyze how lightweight metal alloys are employed.

The first to be used massively on aircraft airframes was aluminum. Still today, between 60 and 80 percent of the commercial airplanes is made of aluminum [126]. Aluminum alloys' designation is based on the alloying elements added to aluminum and on the type of aluminum: wrought or cast. The most widely used on aeronautical industry are the wrought aluminum alloys, namely those based on copper (2XXX series), magnesium and silicon (6XXX series), zinc (7XXX series) and iron, nickel and lithium (8XXX series).

Based on the alloying elements, aluminum alloys adopt different properties and thus are employed in different components. All of these series are heat treatable, high strength and off course relatively cheap as are all aluminum alloys. 2XXX series are used mostly for fuselage skins, as they have good toughness and resistance to fatigue crack growth, and for lower wing skins, being the most widely used the 2024 alloy treated with different heat treatments. Along with 2XXX series, the 7XXX series is also widely used in aeronautical industry as they possess high toughness and the highest strengths of all aluminum alloys and so are used mainly on the upper and lower wing skins.

However they are also quite susceptible to corrosion and are not considered weldable and so must be joined using mechanical fasteners or adhesives. Aluminum alloyed with magnesium and silicon, the 6XXX series, is the least used, of the series considered, in the aeronautical industry. This happens because they possess the least attractive overall balance of properties regardless of having better corrosion resistance, than the 2XXX series, and excellent fabricability and weldability, while both the 2XXX series and the 7XXX series have limited weldability. Nevertheless, a quite recent 6XXX series alloy, the 6013-T3 alloy, has a higher strength and comparable fracture toughness and resistance to fracture when compared to the 2024-T3 alloy, renewing the interest in this series. Their use is limited to lesser stressed components together with other, less used, aluminum alloys series such as series 3XXX and 5XXX.

Finally, the 8XXX series, based on elements not covered on the other series, are quite recent alloys. These alloys introduced the adding of lithium to aluminum which increases the modulus of aluminum while reducing its density. This also enabled the development of 2XXX series with the adding of lithium to Al-Cu alloys. These new alloys especially 2090, 2091 and 8090 are being widely used recently, replacing other alloys of the 2XXX and 7XXX series, as they possess 10% less density and 25% higher specific stiffness. So, they are excellent choices for structural components such as stringers, ribs and longerons, also replacing the heavier steel in some applications [46, 47].

Magnesium was also quite used at the beginning of the metal transition as it is the least dense metal of all. However, corrosion problems and the difficulty to process it held its further employment in the aeronautical industry, to a point that today no structural applications of magnesium exist. Nevertheless, some applications remain. These applications are essentially in complex shaped secondary structures, making use of cast alloys, rather than, as in the case of aluminum, wrought alloys. Being difficult to process magnesium is then used by directly casting the component to be produced. Aluminum and zinc are the principal alloying elements of magnesium providing alloys with interesting mechanical properties.

The reasons for the use of magnesium in aeronautical structures are, mainly, due to the fact that components produced are lighter and have excellent damping characteristics. Corrosion, especially galvanic, and the lack of high strength alloys, still limits the further application of magnesium in the aeronautical industry [47, 123, 127]. Magnesium is thus presented here not because it is widely used but because there are recent developments, that will be presented shortly, which will turn magnesium into a more valid choice for structural applications in the aeronautical industry.

Before looking at the recent developments on these materials, one material remains to be presented in terms of aeronautical applications, titanium. Although titanium is mostly applied on aircraft engines, due to the excellent properties at high temperatures, it is also applied on aircraft airframes.

The main reasons for the application of titanium on airframes are its higher strength-to-weight ratio, its great corrosion resistance and good damage tolerance [128]. So, it is a suitable material to replace steel and aluminum in some high strength applications as it is lighter than steel and stronger than aluminum. These applications include, for example, the landing gear, the floor support structure, ducts, tail cores, springs and some fittings [128, 129]. In most of these applications alpha plus beta alloys are used, especially the Ti-6-4 alloy, accounting for around 80-90% of all titanium used in airframe applications and 60% of all titanium used in aerospace applications. This alloy also possesses superplasticity properties [47]. It is used in most of aircraft's sections such as fuselage, landing gear, wing and tail [129]. Also beta alloys are used to some extent on airframe applications [47]. The most known application of beta alloys was in the fuselage of SR-71 reconnaissance plane [129]. Nevertheless, recently beta alloys have been employed in springs and ducts. The most used of these alloys is the Ti-10-2-3, which is used on landing gears [47].

Yet another use of titanium, in general, is in the areas where contact with composites exists, as titanium has a great galvanic compatibility in contrast with aluminum alloys. So, in this case, fittings and attachments are made in titanium [128]. As for the alpha titanium alloys, they are mainly used mainly in more extreme temperature applications such as anti-icing and environmental control systems' ducts, as they operate at temperatures of about 230°C, but also in hydraulic tubing [129]. However, further applications are limited due to the cost of titanium and so its use is mostly a trade-off between cost and customer value. Weight reduction, lower maintenance cost, due to increased corrosion resistance, and improved reliability are all aspects of customer value that may be used to justify the application of titanium alloys [128].

4.2.5. State-of-the-art of lightweight metal alloys

As it was done for composite materials, various aspects of lightweight metal alloys will be assessed to provide an actual picture of the current technologies in this field. Roughly the same structure, as for composite materials, will be adopted and so, an overview of materials, processes, recycling, inspecting and repairing will be presented.

4.2.5.1. Recent developments in lightweight metal alloys

The development of lightweight metal alloys have a great impact on the aeronautical industry and with composite materials becoming increasingly competitive towards metals, producers of these alloys have all the interest in keeping developing lightweight alloys. The main approaches in developing these materials are mainly to improve their intrinsic properties and counter their downsides. In general new alloys appear constantly with a huge variety of properties. Metal properties are very dependent on the processes used to produce them. So, most properties enhancement techniques will be presented later, together with manufacturing processes. Nevertheless, new types of alloys, the application of new advanced coatings and even the development of new nanomaterials have contributed to provide a wider range of material properties which have increased lightweight metal alloys' competitiveness.

4.2.5.1.1. New alloys and coatings

In aluminum alloys the big developments have been in the field of new alloys, namely lithium ones. As presented, the adding of lithium to aluminum reduces density and raises stiffness, properties of great value for the aeronautical industry. Developments on these alloys have been essentially in order to design the appropriate chemistries and thermo-chemical processing [130]. Recently, however, a new generation of Al-Li alloys has been introduced which further increases savings on weight at the same time that problems with anisotropy of mechanical properties and low toughness, of previous generation alloys, were somewhat overcome [131, 132]. These alloys are now seen as real competitors to composites as they have the advantage of providing, equivalent performance, lower risk and better value as equipment, tools, assembly techniques and training is the same as for conventional aluminum alloys. Furthermore, recycling and repairing are also advantages of these alloys when compared with composites [132].

Another application in the aeronautical industry of aluminum is on coatings. Cadmium coatings, until now very used in the aeronautical industry for component protection against corrosion, have been banned due to environmental and health concerns and so, a substitute had to be found. Aluminum coatings applied by slurries followed by moderate temperature curing has proved to exhibit comparable or better performance and properties than cadmium coatings, meeting aeronautical requirements [133]. Aluminum alloys usually make use of chromium as corrosion inhibitor. However, chromium has an associated toxicity that has made producers look for other solutions. One solution seems to be the use of sodium decanoate which has been investigated on a 2024 aluminum alloy with some success [134]. Another solution is the use of cerium based coatings that has proved to be capable of actively protecting aluminum and magnesium from corrosion [135].

Aluminum has also been investigated as a possible impact absorber in transports. The idea is to use aluminum foams to absorb energy from impacts making use of its lightweight and unique compression deformation characteristics. Still, further investigation is needed as high velocity impacts (≈100m/s) produces responses of the aluminum foam that are not yet fully understood [136].

Looking now at magnesium developments, much has been made to solve its problems, especially when it comes to corrosion. For that, coatings are applied existing different coating processes. However, a new type of coating has been studied as it provides potential advantages: diffusion coating. This type of coating has higher adhesion strength, both electrical and thermal conductivity of magnesium are preserved and may improve not only corrosion resistance but also wear resistance [137]. Also ecofriendly coatings are being developed for magnesium alloys. An example is vanadia based coatings, which has proved to be capable of inhibiting corrosion, being at the same time capable of self-healing [138]. Magnesium surface treatments have evolved at such extension that the corrosion level of magnesium is now comparable to that of aluminum. Other developments, in what magnesium alloys is concerned, are the new Elektron 21 and 675 alloys which have mechanical properties comparable to those of aerospace aluminum structural alloys, thus being real potential alternatives to them, and are less reactive than other magnesium alloys which allows their use for investment casting [127, 139].

Titanium application on aircraft airframes has been limited by its cost. So, most of the research made in titanium has been in reducing production costs [140]. Nevertheless, as titanium is used on the cooler parts of engines, much investigation has been made to enable the use of titanium in hotter areas of the engines. When subjected to high temperatures titanium becomes more reactive with oxygen making it prone to embrittlement. Recently an oxygen barrier has been achieved by the implantation of halogens such as fluorine under titanium alloys subsurface, thus enabling the increase of oxidation resistance up to 900°C [141].

Titanium aluminide alloys is another area of great interest for the aeronautical industry, as the inclusion of aluminum in titanium provides interesting properties. These alloys, also known as gamma alloys, in terms of properties can be found between aluminum and titanium. Gamma alloys possess higher melting point (up to 1000°C) and are lighter than titanium alloys and heavier than aluminum ones. Also in terms of strength they can be stronger than aluminum and weaker than titanium alloys possessing higher modulus than both. An interesting point of these alloys is the fact that their strength increases with temperature. However providing interesting properties their cost still limits their application [142]. These alloys are mostly used in engine parts to replace some superalloys. A potential new application of these gamma alloys is in coating other materials for high temperature oxidation, corrosion and for wear applications, making use of thermal spraying techniques [143].

4.2.5.1.2. Nanomaterials

Nano scale developments are considered to be the next step in what materials development is concerned and advances on lightweight metal alloys, have been made. In aluminum, for example, nanostructure is achieved by inducing very high strains, using severe plastic deformation, in order to refine the material’s grain down to the nano scale. Nanostructuring in aluminum alloys strongly improve mechanical strength but also electrical conductivity and corrosion resistance turning aluminum alloys into more multifunctional materials as high mechanical properties are combined with functional properties. However attractive, only small samples of nanostructured aluminum are produced each time resulting in very high costs. Nevertheless, recent efforts are being made to counter these issues [144].

Nano scale developments have also been made in magnesium but in metal matrix composites using magnesium as matrix. The inclusion of nanoparticles in magnesium matrices, using ultrasonic and acoustic methods to obtain proper dispersion of particles, has been demonstrated to produce high performance magnesium nanocomposites, imparting an excellent combination of strength and ductility [145, 146].

Investigation in what nano scale titanium is concerned, has been mostly towards achieving titanium powder and layers in the nano scale level in order to make use of titanium's properties, such as high strength and resistance to corrosion and high temperatures, in composites or as coatings [147, 148]. These powders then have a various ways of being applied with the purpose of producing titanium coatings on other materials. Electrochemical deposition, thermal sintering and vapor deposition are among the most used processes for applying titanium coatings. Another method for producing open porous titanium coatings is the vacuum plasma spraying (VPS) which is a very rapid and cost efficient method although many times mechanical stability is not frequently achieved [149].

4.2.5.2. Manufacturing processes for lightweight metal alloys

Manufacturing processes for lightweight metal alloys include various types of processes that can significantly change the properties of the metals. So, one can divide these processes in those involved in enhancing metal properties and in shaping them. Further types of processes exist such as those for finishing and assembling metals. Finishing processes have the purpose of improving the appearance of metals, by, for example, painting, and providing protection, mainly to corrosion, by using coatings [45]. Finishing processes were already addressed. Assembling processes will be addressed later.

4.2.5.2.1. Properties enhancement

This type of processes, as the name suggests, are processes in which the properties of a material are improved in a desired manner. These processes can be further divided into alloying, cold working and heat treatments [45]. Alloying has already been mentioned and consists in combining two or more elements in which at least one is metallic to obtain a final material with different properties. In cold working, strains are induced to the materials, whether in pure form or in alloys, to alter strength and ductility. The induction of strains is accomplished during deformation of the material using one of the shaping processes, such as rolling, forging or extrusion. Hence, the strengthening of the material occurs as a by-product of the shaping operation [45]. Furthermore, there are processes in which the deformation of the material does not occur. In these cases, such as in the peening process and in sandblast, the shaped material is impacted with sand, in the case of sandblast, or round particles, in the case of peening, to produce a compressive residual stresses layer and modify the mechanical properties of the material.

For instance, a new shot peening process, fine particle shot peening (FPSP), has been applied successfully not only to reduce residual stresses but also to enhance fatigue life of aeronautical aluminum alloys. This process is in general similar to conventional shot peening with the difference of being the higher blowing velocity and the finer particles expelled [150]. As for heat treatment, they consist in several heating and cooling cycles performed on the material in order to alter its basic microstructure which determines the mechanical properties of the material [45].

Heat treatments can be performed on the metallic components repeatedly during its cycle of manufacturing, although they can also be applied before the components takes its shape in order, for example, to soften up the metal so it can be easily shaped. Furthermore, heat treatments can also be used to relieve the part from strains induced during forming so that the component can sustain further deformation [45]. In what lightweight metal alloys is concerned, annealing and precipitation hardening (mostly solution treating and aging) are the most used heat treatments [47].

Annealing is a process in which metals are heated up and held at a relatively high temperature for a certain period of time and then slowly cooled. Through this process one can reduce hardness, obtain different mechanical properties, soften the metal to facilitate its machinability and formability, recrystallize cold worked metals making them tougher and to relieve residual stresses induced by prior processes [45]. In aluminum this process is used to mainly to increase ductility as well as magnesium. Magnesium alloys have a limited ductility and in order to improve that property, alloys are usually subjected to some cold working, mainly rolling, being afterwards heat treated to relieve strains caused by that process. Recently a new process to increase magnesium ductility is based on using laser scanning treatment to weaken magnesium's surface structure thus making it more ductile while maintaining strength properties [151]. In the case of titanium various processes exist depending on the desired effect. The widely used in the aeronautical industry, Ti-6-4 alloy is mostly mill annealed with the purpose of increasing strength and ductility. Other effects of annealing exploited in titanium alloys are the increase in toughness and creep resistance [47].

To harden and strengthen metals, precipitation hardening is applied, being the most used heat treatment process to strengthen alloys of aluminum and magnesium. It consists of three steps: solution treatment, which consist in heating and holding the metal to a temperature in which it has a different phase than the initial, quenching, in which metal is cooled to room temperature to create a supersaturated solid solution, and aging where metal is again heated and held at a temperature below that of solution treatment before being cooled at a lower rate than in the quenching process. This process can deliver results similar to those obtained with annealing if the aging process is longer (overaging) [45].

For aluminum alloys, in order to be possible to apply precipitation hardening, which greatly increases aluminum alloys' strength with a small reduction in elongation, two conditions must be met. First, the alloy must contain at least one element or compound in sufficient amount that has a decreasing solid solubility in aluminum with decreasing temperature and secondly, the element or compound must be capable of forming a fine precipitate. Alloys that meet these requirements are said to be heat treatable and consist in the 2XXX, 6XXX, 7XXX and 8XXX, obviously the most used in the aeronautical industry.

Although not attaining as high strength as aluminum alloys, casting magnesium alloys can be treated to reduce embrittlement and improve ductility. In the case of titanium, only the beta plus alpha and beta alloys can be subjected to precipitation hardening, being beta alloys more susceptible to heat treatment and so can achieve higher levels of strength, hence their use in airframe applications. The problem with titanium is the fact that when subjected to high temperatures it becomes more reactive with oxygen and so coatings are applied to prevent this from happening [47]. Still, in what titanium is concerned, and in order to improve its hardness, strength and wear resistance, boriding can be applied, although it is more commonly applied to iron. Boriding is a thermal diffusion process in which boron atoms can diffuse into the work piece to form a range of metal boride phases in order to change the piece's surface and give it the increase in properties mentioned above [152].

4.2.5.2.2. Shaping processes

As the name suggests these processes are responsible for shaping metals, in this case, and can be further divided into casting processes, forming processes and machining. Among them are the above mentioned cold working processes. Some of these processes are quite ancient dating to several centuries ago. Nevertheless, other recent methods have been developed taking advantage of developments in other fields of science. The approach adopted in the section regarding composite materials will be followed here and so only a brief presentation of the shaping processes will be made, as there is a vast literature for these processes.

4.2.5.2.2.1. Casting

Metal casting processes can be divided into two categories: expendable mold or nonexpendable mold. Casting consists mainly of pouring molten metal into a mold in order to obtain a component. So, depending on the way molten metal is poured into the mold and on the mold's material one can further divide casting processes. The main advantage of these processes is that it enables the production of more complex shapes in one component that would require several parts if other means were used. On the downside, casting processes are very prone to defects. Expendable molds may imply a lower production rate as the mold is lost after the production of one casting, however, the possibility to reduce part numbers, and hence cost, time and weight, can be very attractive [45, 129]. In what aeronautical components is concerned the most used casting processes are those listed in table 2.

Name	Advantages	Disadvantages	Description	Materials
Sand Casting	- Very versatile - Low cost	- Lower mechanical properties - Wider tolerances	The sand mold is made by compacting sand in a wooden crate in two halves. Molten metal is then poured into the closed mold.	- Aluminum - Magnesium
Plaster and Shell Molding	- Good tolerances - Smooth surface	- Lower mechanical properties than sand casting	The process is equal to sand casting except gypsum plasters replace sand.	- Aluminum
Permanent Mold Casting	- Good mechanical properties - Good tolerances - Smooth surface	- Higher cost - Short mold life - Limited to low melting point metals	The liquid metal is poured into a metal mold and allowed to solidify.	- Aluminum - Magnesium
Die Casting	- High rate of production - Excellent tolerances and surface - Complex shapes	- Not very high mechanical properties - Higher cost - Limited to very liquid metals	The liquid metal is injected into molds at high pressure.	- Aluminum
Investment Casting	- Good surface - Excellent tolerances - Thinner walls	- Surface contamination can occur	A first mold (pattern) is produced from wax which is then coated with ceramic. Wax is then melted and taken out being replaced by the molten metal to form the component. Ceramic is broken and the component retrieved.	- Aluminum - Magnesium - Titanium
Evaporative Pattern Casting	- Complex shapes - Good tolerances	- Low mechanical properties	In this process the mold evaporates when metal is poured into it.	- Aluminum

Table 2 – Most used casting processes in the aeronautical industry and their advantages, disadvantages, description and application [45, 47].

From these processes die casting and investment casting are the most widely used in the aeronautical industry. Developments in what casting is concerned are essentially towards increasing the quality of components produced, whether by modeling cast defects or by tuning the cast process. As seen, porosity in casting processes is a very likely defect to happen. This is mainly due to the slow rate of cooling and shrinkage of the material during cooling which can trap gases on the inside. So, recently multiscale models have been developed to provide designers with a tool to better tune the casting process in order to obtain higher quality components, having proven to be quite accurate [153].

In the case of investment casting much has been done to improve it, turning it into a very used process even in the aeronautical industry as high quality components are possible. These advances are essentially the increased recovery of wax via microwave or infrared heating, the incorporation of fibers into the ceramic coating to improve permeability and the use of rapid prototyping techniques, such as laser sintering, to quickly produce patterns with increased finishing quality and geometrical accuracy [154].

Advances in die casting have produced at least two important variants of the process: squeeze casting and thixotropic casting. In squeeze casting molten metal is filled into a steel mold at high pressure but at slower rate. This causes the components to have no porosity and can be welded and heat treated. As for thixoforming it consists in producing a bar by continuous casting which is then cut into billets, heated by induction and then press formed in a mold to produce a component with lower porosity and more uniform microstructure (Figure 4.11) [155]. Continuous casting is a process in which bars or billets are produced by pouring molten metal into a long mold with rolls. As the metal solidifies first near the walls it allows the bar to hold together until cut to size [156]. One of these processes, twin roll casting, has been proved to be capable of producing sheets of magnesium with low porosity. Molten metal is poured along a cooling slope that will plastify the metal which is then driven through two rolls to form a sheet [157].

4.2.5.2.2.2. Forming

In forming, the component is manufactured by deforming the initial workpiece, compacting and sintering the powder or molding the material into the desired shapes using tools that apply stresses greater than the yield strength of the material to plastically deform it. The shape is determined by the geometry of the tool [45, 158]. The high stresses applied to the materials produce the already mentioned strains that will alter the materials' properties.

Forming processes can be divided into two categories: bulk deformation processes and sheet metalworking processes. Bulk describes workpieces that have a low area-to-volume ratio. So, bulk deformation processes are those that shape billets and bars. Processes like rolling, in which the workpiece goes through rolls to reduce thickness, forging, that implies heating the workpiece and subject it to a high compression force between two opposing dies, extrusion, to produce components by pushing the workpiece to go through a die, and drawing in which the workpiece is pulled through a die. As for sheet metalworking they include bending, drawing and shearing (cutting) [45]. These are the more traditional processes that have been known for a very long time along with powder metallurgy. In addition another category can be considered, superplastic deformation.

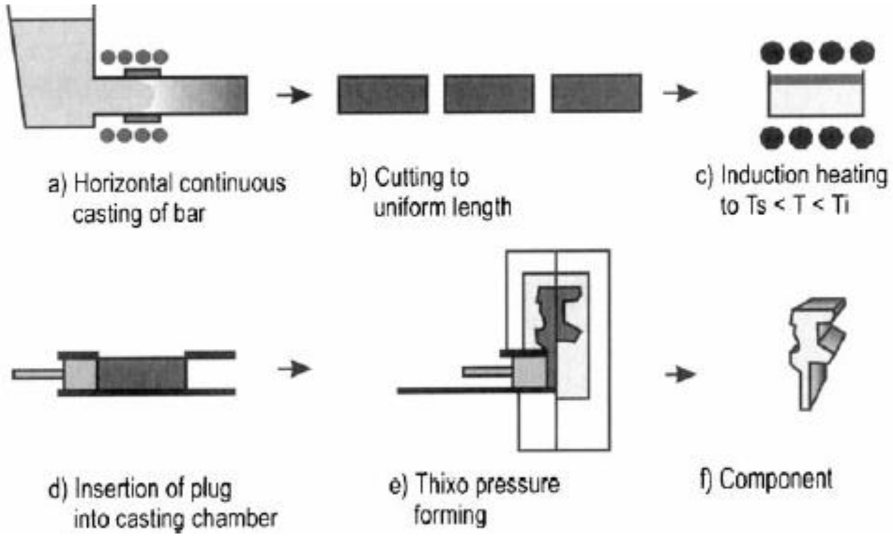


Figure 4.11 – Principle of thixoforming [155].

Powder metallurgy involves the compaction, in rolls or dies, of fine powder into a desired shape followed by high temperature sintering (lower than melting temperature) to produce components with close tolerances using materials that are difficult to shape to the desired form otherwise. Furthermore, these processes can be automated, can produce net shape components and involves very little material waste. On the downside equipment cost can be quite high and metallic powders are expensive and can degrade over time, requiring special attention in what storage is concerned [45, 159].

Superplasticity is a property of some metallic alloys with fine grain size that allows sheet to elongate to quite large strains without rupture or localized necking. Superplasticity occurs at temperatures at around half the melting temperature and can produce deformations of up to 1000% greater than the typical limit of the material. Nevertheless, superplastic forming processes are limited to deformations in excess between 100-300%. The advantages of this process are the possibility of producing shapes not possible or not feasible with other methods, the stresses in these processes are lower, no springback is induced to the material and machining costs are low. These processes allow the production of components with double curvature. As for the disadvantages, superplastic forming is a rather slow process and equipment and tooling can be quite expensive. The process itself is a rather simple one: a sheet of metal is placed inside a die and heated to half the melting temperature, afterwards a gas is injected into the die forcing the sheet of metal against the walls thus shaping it. Variations exist as different gases can be applied and the injection of gases can occur in different places inside the die. As said, not all alloys possess superplastic properties. In the aeronautical industry aluminum and titanium alloys are the most used materials in superplastic forming, although titanium exhibits higher plasticity than aluminum.

For titanium alloys, superplastic forming can be combined with some bonding processes to produce unitized components. This is made by stacking titanium sheets, ranging from two to five or more, and bonding them in specific locations so that when gas is applied, the bonded locations are stretched forming an internal structure for the component [47]. This process is quite used to produce several components for the aeronautical industry such as the Eurofighter's slat which is produced using six sheets of a titanium alloy that is bonded in certain locations and once inside the die and under the right temperature a gas is inserted laterally inside the set of sheets. The result is a complete slat with internal reinforcing structure.

Advances in these processes are mostly to accompany those occurred in materials. As progress in materials are towards increased strength, strain is generally lower and so, high strength materials require forming processes capable of producing higher deforming forces, in other words, forming processes need to increase their formability and flexibility [159]. At the same time, forming processes strive to reduce the environmental impact, reduce the waste in material, the process steps and tooling costs. For this, machine control algorithms have proved to be effective in dealing with various materials to reduce the mentioned aspects [160].

4.2.5.2.2.3. Machining

Machining processes for metal are techniques in which material is removed by the use of a tool in conventional machining processes or by other means, the so called nontraditional machining processes. In the aeronautical industry both types of machining processes are employed quite extensively. As for the methods themselves, there is a huge number of them each providing a different texture or part geometry [45].

Starting with the conventional processes these can be further divided into: turning, in which the part is rotating and a tool, which moves parallel to the part and inwards, cuts the part by action of speed to generate a cylindrical shape, drilling, that as the name suggests creates holes using a rotational tool, and milling in which the tool is also rotating and moves throughout the surface of the part to produce a plane or straight surfaces [45, 129]. Like most of the forming processes, machining processes have accompanied Man for many centuries, as they are also used for woodworking, and advances in them have been few, essentially to improve their cutting efficiency, making use of new stronger materials for the tools, and to automate them enabling more precise works via computerized tools, which can be referred as rapid prototyping.

Nontraditional processes are the more recent processes that have been developed to cope with the newer materials such as composite materials and high strength metal alloys. The advantages of these processes, in general, are that they allow very tight tolerances and complex shapes, they can machine very hard materials, and avoid the rise in temperature and the appearance of residual stresses. These processes make no use of a cutting tool. On the contrary they use mechanical, thermal, chemical or electrical energy to remove the excess of material. The most used nontraditional machining processes in the aeronautical industry are ultrasonic and water-jet (mechanical energy), laser beam machining and arc-cutting (thermal energy) and chemical machining [45, 129].

A quite recent process capable of producing microcomponents is known as photochemical machining. In this process a wet chemical etchant is applied through apertures fabricated in a photoresist stencil which allows the removal of the selected material with a performance comparable to that obtained via laser beam machining but at a lower cost. In a study conducted with magnesium a micro air vehicle wing was manufactured with very tight tolerances of just tens of millimeter [161].

Until know subtractive manufacturing has been addressed, in the sense that all these processes remove material, however, a new type of processes have quite recently been developed for metals. This new type is known as additive manufacturing. In these processes the necessary time to produce a component is drastically reduced at the same time that tools needed for the job are also reduced in number. Although various types of these processes exist, mostly for plastic materials, for metals they are essentially those categorized as granular methods. Direct metal laser sintering (Figure 4.12) and electron beam melting are the most used for metals.

In these processes a computer model is fed to the machine which will use metal powder, which is then melted using a laser or an electron beam, in these cases and placed layer by layer on a surface to form a component. These thin layers makes that the resulting component does not need further machining. In the case of electron beam melting it occurs in vacuum thus preventing some metals such as titanium from reacting with oxygen. Besides titanium, in what lightweight metals is concerned, also aluminum is widely used [45, 162, 163]. Another method has been developed for the rapid prototyping of metals, ion fusion formation. In this low cost method a very hot ionized gas deposits metal in small discrete amounts and subsequently builds a complete part. Components can be used as-deposited or can suffer further treatments or further machining [163].

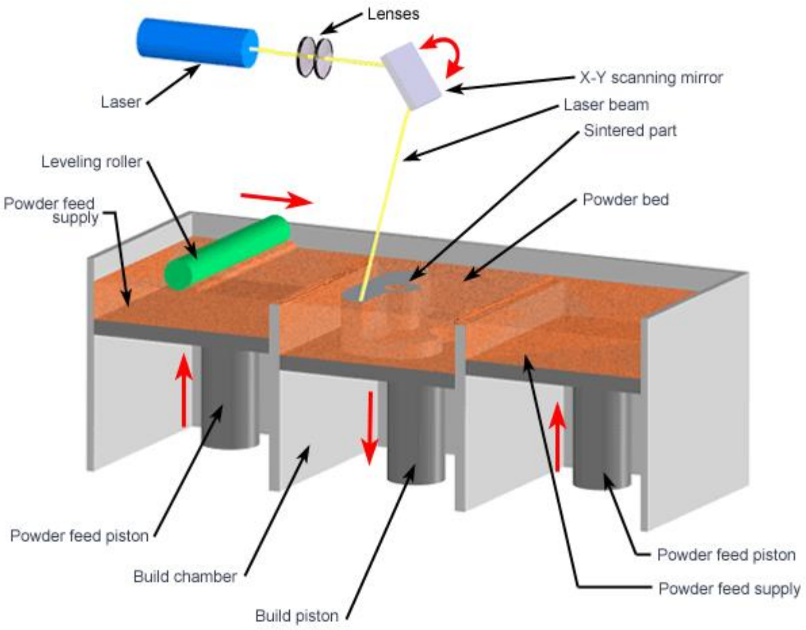


Figure 4.12 – Principle of the direct metal laser sintering process.

Source: http://www.custompartnet.com/wu/direct-metal-laser-sintering

4.2.5.3. Joining methods for lightweight metal alloys

Joining methods for lightweight metal alloys are the same for normal metals in general and so include mechanical fasteners, welding, brazing and adhesive bonding. Nevertheless, depending on the material and alloy some methods are not used. For example, the aluminum 2XXX and 7XXX series are not brazed, as their melting point is too low for successfully apply this method. Mechanical joints, those using rivets and bolts, are the most used as they are easily applied and facilitate disassembly for repair, in contrast with welding which use is very dependent on the material. The wide use of mechanical fasteners in the aeronautical industry has to do with the fact that most of the aircraft is made out of aluminum, which can be rather difficult to weld, being susceptible to cracking and distortion after it.

Furthermore, the need to join components of different materials sometimes does not allow welding. On the contrary, titanium is a very weldable material, although some care is essential as to prevent contamination from the atmosphere due to the high reactivity of titanium with oxygen when at high temperature. Also magnesium is quite weldable, although alloys with high content of zinc are not, as aluminum, being very susceptible to crack after welding. As for adhesive bonding, as already presented for composite materials, it is a fairly recent method that is now quite spread in what industrial applications is concerned [45, 47].

Literature on this subject is vast and so a lot of information regarding all welding, mechanical fasteners and adhesive bonding methods can be found. So, here it will be presented the most recent and relevant advances in these technologies.

The advances in joining methods for lightweight metal alloys can be assumed to be the advances made in the technologies themselves, although, in the case of welding, some are subsequently adapted depending on the material. Most of the many relevant advances made in joining methods have occurred in the field of welding and adhesive bonding. As adhesive bonding was already discussed in the section related to composite materials, only the advances in welding will be presented here.

Nowadays, welding is evolving towards further automation, enabling the use of welding processes in a wider range of materials and applications, and towards new processes. A quite recent process to the aeronautical industry is Friction Stir Welding (FSW) which consists in a rotating tool that will, when in contact with the material, generate heat that will soften the material to a plasticized state thus enabling the bonding between the two parts. This process has been proved to allow high quality welding for a variety of materials including the problematic aluminum and has since a few years from now been applied successfully in the aeronautical industry [164]. A recent innovation to this process is the self-reacting pin tool which provides more design option as the pin goes through the material and has another piece on the other side not being necessary another surface on the bottom (Figure 4.13) [165].

Also on the field of solid state welding, a process making use of magnetic pulses has been developed. In this process two parts are welded using very strong opposite magnetic forces that are generated around each part to force them into one another. Forces are so high that joining occurs without any exchange of heat. Studies conducted have successfully been able to produce bonding of different materials such as aluminum with magnesium or aluminum with stainless steel. Nevertheless, its use in the industry is still experimental [166, 167].

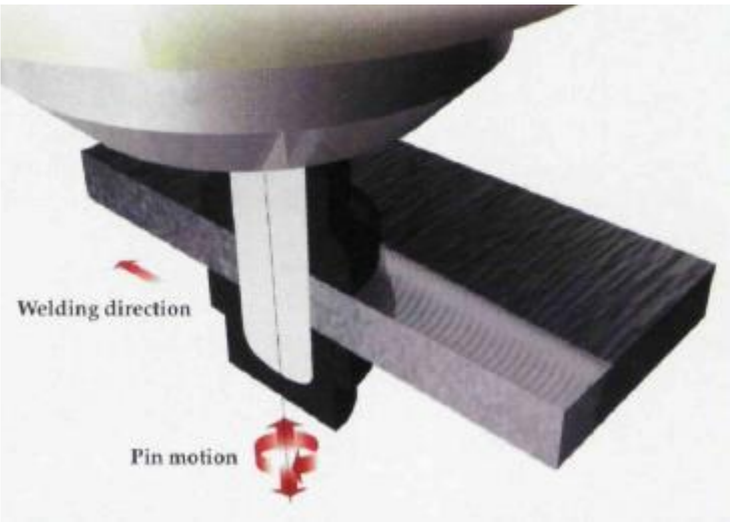


Figure 4.13 – Schematic of self-reacting pin tool variation of FSW [165].

Advances in the field of fusion welding have also occurred in the last few years. In joining steel and titanium, conventional fusion welding is not advised as the formation of brittle intermetallic compounds occur. So, solid-state joining is the most feasible way of joining these two metals. However, the use of spark plasma sintering has proved to be capable to strongly join different types of metals. Heat, in this case, is generated internally by the passing of a pulsed DC current promoting the bonding of the materials. This process is still in its first stages of development as many aspects of the process itself are not yet understood [168]. Also on the field of fusion welding, laser welding has been the focus of much investigation in order to further apply it to the aeronautical industry, hence following the mentioned goals of development, as it provides welding with very high quality in terms of welding properties and strength. So, laser welding has been applied successfully in some magnesium alloys thus enabling the increase in their use on the aeronautical industry [169].

Another relatively new field in welding is hybrid welding (Figure 4.14). In this type of welding two heat sources are coupled acting on the weld pool simultaneously. This allows the use of the advantages of both while minimizing the disadvantages. The most used in the industry is laser coupled with either MIG or TIG, although other processes exist such as laser-plasma, laser-light, laser-shielded arc and laser-induction welding. The operating principles of these processes are basically the adding up of each one’s operating principle. Recently a study comparing conventional laser welding with laser-MIG welding has demonstrated that a better combination of strength and ductility can be achieved with laser-MIG for a titanium part [170, 171].

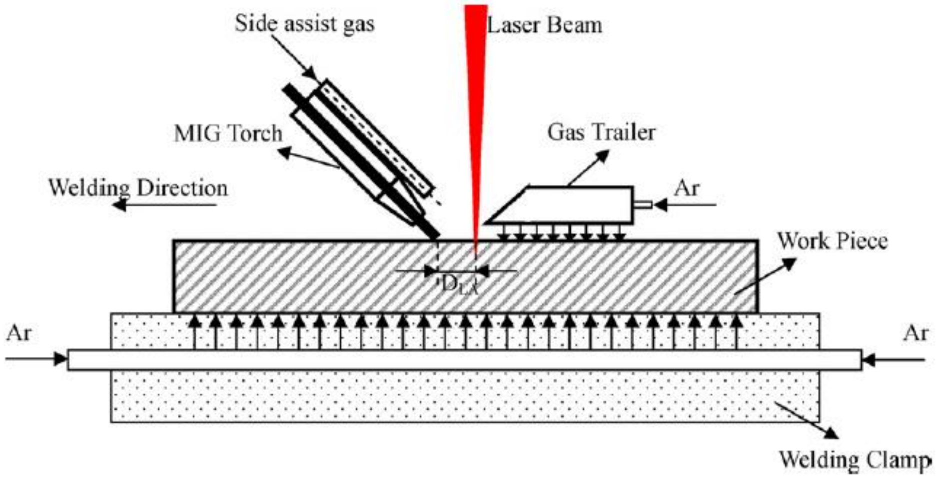


Figure 4.14 – Setup of laser-MIG hybrid welding [171].

4.2.5.4. Recycling of metallic structures

Nowadays the management of end-of-life aircraft is a very serious issue for aircraft owners as the possibility to economically valorize components, by selling scrap, can be an attractive one. It is believed that 90% of an aircraft can be reused, remanufactured or recycled [172]. Looking at metal components they can be either reused in less demanding applications, remanufactured by replacing some items of the component by new ones or recycled. In recycling metal components are disassembled and the different parts shredded or separated via mechanical, gravitational, centrifugal or magnetic methods. After being sorted out, metal items are then remelted for recast or are returned to a blast furnace for re-purification of the materials [173].

Nevertheless, the valorization of materials and components of an aircraft rarely reach 60% due to the lack of infrastructures and process inefficiency. Currently, aircraft airframes are cut and crushed, after being stripped of contaminating components such as fuel and electronic equipment, thus obtaining scrap. Scrap is then a mixture of metals, mainly aluminum. With an high degree of impurity, due to the various alloying elements present, the metals obtained by remelting this scrap cannot be reused for high demanding applications and so must go to less demanding ones [172]. Nevertheless, the general feeling is towards recycling as in some cases, recycling light metal alloys from scrap only requires as much as 5% of the energy consumed when they were first produced and materials do not lose a substantial amount of properties as occurs for composite materials [174]. For example the amount of primary aluminum produced could be reduced to less than the current level by using greater quantities of scrap [175].

So, the importance of sorting out materials and components is paramount in order to obtain materials with higher levels of purity. However, for that to happen, both recovery and processes must be optimized in order to, on one side to avoid the mixture of metals and on the other to enable the re-purification of those metals. Some approaches are being developed in order to optimize the entire cycle of dismantling, reusing and shredding [172, 176]. As for the processes of recycling metals with impurities, they rely on chemical and hydrometallurgical methods, although these processes are complex, with high energy consumption and are low productive [175].

An approach on magnesium alloys is to use a process called rheo-diecasting to directly recycle magnesium scrap. When die-casting magnesium, only a portion of the material input ends as a final product, while the rest is considered scrap. With the rheo-diecasting process a mixture of primary alloy ingots and scrap was successfully used to produce a high integrity magnesium alloy casting without any significant loss of properties and with proper chemical composition. Rather than eliminating the impurities, these were treated physically under intensive forced convection to eliminate the harmful effects of the impurities [175].

Another approach to magnesium recycling is to create nanofibers from magnesium waste using hidriding chemical vapor deposition (HCVD). This process has been demonstrated to be able to produce MgH_2 nanofibers with high purity from all types of magnesium scrap. The interest in these fibers is mostly in the batteries industry, as MgH_2 is a very promising material for Li-ion batteries and as hydrogen storage material allowing increased energy storage [177].

As for titanium recycling, the problems are mostly the same: the contamination by alloying elements. Studies have demonstrated that only some elements can be successfully removed from titanium scrap. Magnesium and some rare earth metals are the only ones who can be removed to the slag by oxidation, while other elements can be removed by evaporation. Still, aluminum and iron among other major alloying elements tend to stay on the molted titanium and are difficult to separate [178]. Nevertheless, after some cleaning and refining procedures, high quality titanium scrap can be used to make ingots for high demanding application if the final remelting step is done by vacuum arc remelting. If the scrap cannot be used for high end purposes it can still be used in other applications [179].

In the field of hybrid materials, although being recent, recycling has also been a matter for discussion. The most widely used of these materials is clearly GLARE and so recycling these materials is of interest. For that GLARE is delaminated thermally and the obtained aluminum sheets can then be recycled conventionally using molten salt to recover the 2024 aluminum alloy [180].

4.2.5.5. Repair of metallic structures

Every structure on an aircraft is subjected to periodic inspections in order to assess their condition in terms of continued airworthiness. Once a defect is detected three things can happen: the component is not repaired, as the defect is too small and therefore will be monitored, the component is repaired or the repair is not economically viable and so the component is replaced by a new one. If repair occurs, for metallic structures, it is done either by applying a patch or some sort of reinforcement in order to restore structural capability or, in the case of minor damages, the removal of the damaged area is done, for example, by grinding. If the damage goes too deep in the component, the removal of the defect can cause component thickness to go under the one allowed by the manufacturer and thus the component becomes useless having to be replaced. As for patches they consist mostly in what was already presented for composite materials. So, the load path weakened or removed by damage or cracking is restored using metal plates, usually of the same alloy as the parent material to avoid corrosion, which are bolted or riveted [181]. Nevertheless, titanium patches have been successfully applied to aluminum wing skins.

However, in contrast to the usual approach in metals and similar to the approach taken for composite materials, adhesively bonded repair, making use of polymer adhesives, are becoming ever more applied. The reasons for the use of this type of repair lies in the fact that they do not need extra drilling and do not add as much weight to the structure as mechanical repairs. In addition loads are better transferred and distributed along the reinforcing plate with adhesive bonding. In short, adhesive bonds provide a very stiff and efficient reinforcement. The question arising is, should the patch be composite or metal? Composite patches can provide a more optimized, lightweight and strong solution, however, thermal solicitations may limit their application as they have a quite different thermal expansion coefficient than the metals they are «repairing». Being a quite recent technique, adhesive bonds still need to be verified. For that, various NDI processes can be used, mostly those already covered in the composite section such as ultrasonic methods [181, 182].

Another technique for metal repair has been developed. The cold spray technique consists in spraying a powder at high velocity using a heated gas (air, nitrogen or helium) over a surface to create a coating (Figure 4.15). Applied to repairing, this process applies a deposit of material on the area to be repaired which is then machined to the desirable shape of the component. Cold spray has been proved to recover a number of magnesium and aluminum components with economical and technical advantages over the more traditional methods. Still, further work is needed in order to qualify cold spray for high value aircraft components made of aluminum and/or magnesium [183].

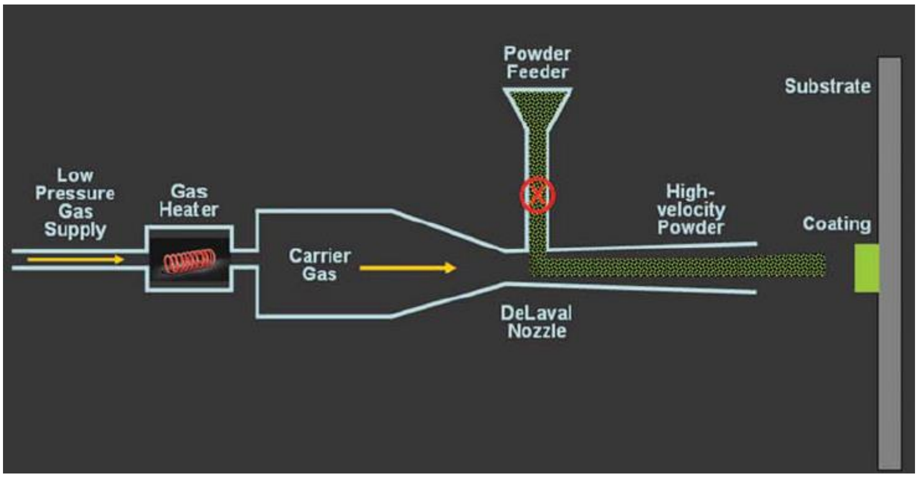


Figure 4.15 – Schematic of the Cold Spray process [183].

4.2.5.6. Non-destructive Inspection of metallic structures

After a production and during maintenance, components need to be inspected both externally and internally for damages or defects, preferably without breaking them. For that, non-destructive inspection processes are used. In metallic components this inspection is made using some of the processes already discussed for composite materials, as they are usually designed for isotropic materials, such as metals, not only to assess the materials' integrity but also to assess the condition of welding. Typical NDI processes for metals include visual inspection (penetrant liquids and magnetic particles), radiography, Eddy current, ultrasonic and optical methods and thermal imaging [46, 184]. The use of these processes is widely documented for a multitude of materials including those treated here.

Nowadays advances on these processes are essentially to further improve their reliability, accuracy, simplicity and to reduce their costs [46]. For instance, X-rays and thermal imaging can now provide three-dimensional images of the internal defects in metallic components, even intergranular corrosion [46, 185]. As for time reduction, a quite recent process, photon induced positron annihilation, has been demonstrated to effectively evaluate fatigue damage or microcracking in fastener holes without removing the fasteners [131]. This method makes use of the positron-electron, induced by a linear accelerator, annihilation energy that is analyzed to determine whether the annihilation occurred on a damaged or undamaged area, providing very accurate results even at atomic level before cracks start to spread [186].

Such as for composite materials, continuous monitoring of the condition of components has also been a concern for metals and so, sensors making use of Eddy current have been discussed with major manufacturers and airlines in order to determine suitable applications for these sensors and to flight qualify them [131]. Other advances in Eddy current have been in order to improve image processing making use of bi-dimensional filtering techniques which improves accuracy [187]. Also, Lamb waves have been investigated to detect corrosion and even assess the loss of material due to corrosion at the same time that foundations were laid to the development of fast wide area inspection technique for corrosion detection in plate-like structures [188].

Nevertheless, it is on image processing and combination of images that most developments have been made, making use of the developments in processing images by computer. For this, additive models are used to combine the images. These models are general, in a way that they can process images from different processes [189].

4.2.5.7. Conclusion

Throughout this section composite materials and lightweight metal alloys were presented as well as their recent developments. During this assessment, the difficulties of applying these materials were also highlighted. Composite materials, although becoming the most used type of materials in aircraft construction, there are still problems that somehow limit their use, such as those described for repair, inspection and recycling. Nevertheless, the developments made in dealing composite materials’ disadvantages are substantial and promise to enable the further employment of these materials in aircraft construction as replacement of lightweight metal alloys. These, however, have been developed essentially to take further advantage of their intrinsic properties, that enable their use for specific applications in which composite materials are not feasible possibilities. So, the question, to which this work hopes to contribute for an answer, is at what extent composite materials can and/or will replace lightweight metal alloys in the airframe of an aircraft. The selection of materials and manufacturing processes is not restricted to which materials/processes have the best properties and allow the faster or better quality in component's manufacturing. For this selection, a variety of other factors need to be evaluated to determine their viability, especially when considering new technologies.

5. Technology adoption in the aeronautical industry

Before looking at the expected and feasible ways for technological advances in materials and manufacturing processes and their application in the aeronautical industry, it is important to assess how these advances are incorporated in the production of an aircraft. For that, we need to look at the aircraft's design process and, from it, identify the stages at which the mentioned advances can be taken into account and, thus, identify the obstacles to those changes.

From what was already presented, operational costs and production time to customer have been made, in the recent years, very important topics of discussion. The operational phase of an aircraft represents a great part of the aircraft's life cycle (Figure 5.1). However, it is the design phase of the product that defines the conditions of production and operation [190]. Narrowing even further, it is the detailed design phase that has the greatest impact on costs and time to customer/market, as manufacturing details are added to enable the production of the aircraft. These details include the materials, and consequently the processes, to be used to produce the aircraft [191].

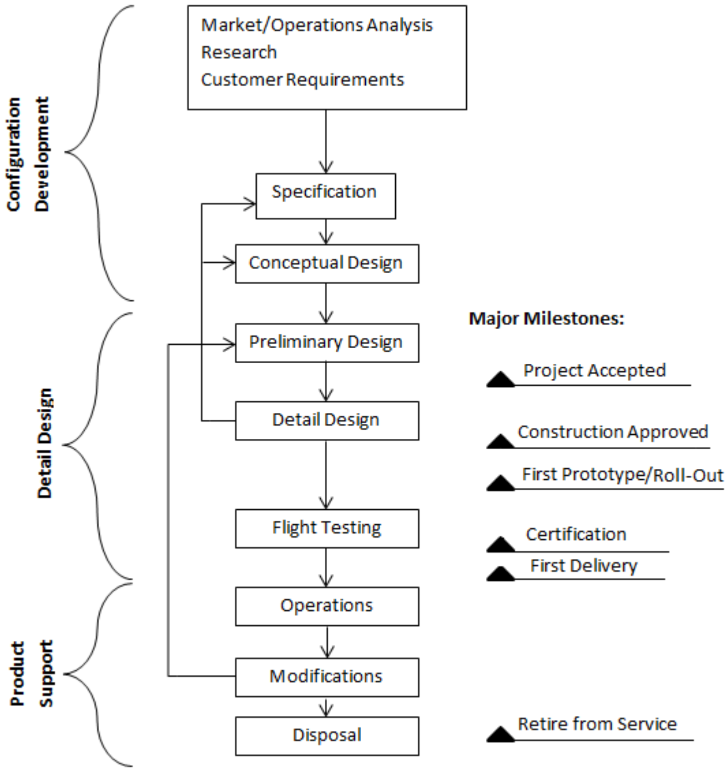
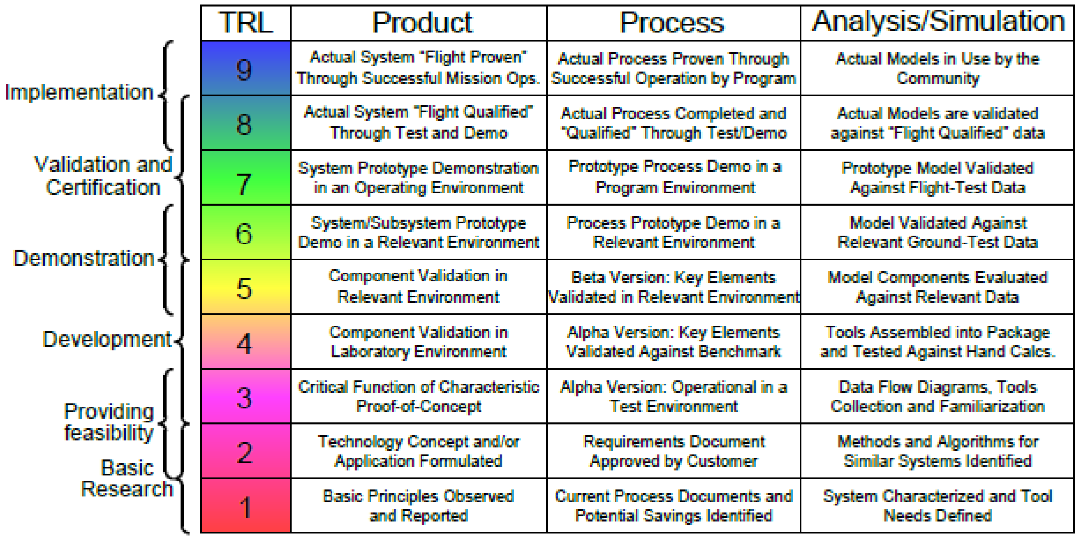


Figure 5.1 – Aircraft Design Process.

This phase of design with the purpose of enabling the series production of a product is called industrialization. The industrialization of an aircraft has essentially two goals: to obtain the aircraft's certification (Type Certificate, TC) and, as said, to enable the series production of the certified aircraft. Therefore the industrialization is a significant step in the life cycle of the product. During this process, all components have also to pass on the tests (First Article Inspection, FAI) made to ensure that all engineering, design and specification requirements are correctly understood, accounted for, verified and recorded [192]. This way we find our first obstacle to the introduction of new technologies: aeronautical regulations. To note that regulations are not an obstacle themselves, but due to the need of observance they can be seen as a barrier to be overcome during the design and certification process.

So, every new manufacturing process and material needs to be tested and certified to guarantee that the design and production requirements, of the components to be produced, are met depending, obviously, on its application, i. e., for a structural component, design requisites are tighter, as these components are crucial for flight safety, in contrast with the requisites for a secondary structure. In practical terms, the difference, in this case, between a new and a traditional process/material is the number of design iterations needed for a component to pass on the FAI, as with traditional processes/materials knowledge and experience exists which, in turn, will result in less costly and time consuming corrections and hence lesser iterations to FAI [164]. So, the application of a new process/material has to do with knowledge and experience available in their use. In what the aerospace industry is concerned and in order to reduce life cycle costs it is fundamental to use new technologies with some degree of maturity [193]. We then arrive to another concept relevant to assess the application of new technologies, the technology readiness level (TRL) [164].

The maturity of technologies has been a concern for different research and governmental agencies, resulting in a 9 level scale proposed by NASA, further developed by Boeing (Figure 5.2), and taken in consideration by the European Defense Agency, to quantitatively assess not only the product's maturity but also processes' and analysis and simulations' maturity [194]. Therefore, the purpose of these scales is to assess the maturity of a given technology, component or system from a certain perspective, existing different scales depending on that perspective, for example, manufacturing (Manufacturing Readiness Level), integration (Integration Readiness Level) or even from the human point of view [195, 196]. Nevertheless what is intended to be presented here is the idea of the importance of a certain technology's maturity, whether a manufacturing process or a system, in the detailed design phase and its repercussions on the production of the final product.



TRL	Product	Process	Analysis/Simulation
9	Actual System "Flight Proven" Through Successful Mission Ops.	Actual Process Proven Through Successful Operation by Program	Actual Models in Use by the Community
8	Actual System "Flight Qualified" Through Test and Demo	Actual Process Completed and "Qualified" Through Test/Demo	Actual Models are validated against "Flight Qualified" data
7	System Prototype Demonstration in an Operating Environment	Prototype Process Demo in a Program Environment	Prototype Model Validated Against Flight-Test Data
6	System/Subsystem Prototype Demo in a Relevant Environment	Process Prototype Demo in a Relevant Environment	Model Validated Against Relevant Ground-Test Data
5	Component Validation in Relevant Environment	Beta Version: Key Elements Validated in Relevant Environment	Model Components Evaluated Against Relevant Data
4	Component Validation in Laboratory Environment	Alpha Version: Key Elements Validated Against Benchmark	Tools Assembled into Package and Tested Against Hand Calcs.
3	Critical Function of Characteristic Proof-of-Concept	Alpha Version: Operational in a Test Environment	Data Flow Diagrams, Tools Collection and Familiarization
2	Technology Concept and/or Application Formulated	Requirements Document Approved by Customer	Methods and Algorithms for Similar Systems Identified
1	Basic Principles Observed and Reported	Current Process Documents and Potential Savings Identified	System Characterized and Tool Needs Defined

Figure 5.2 – Technology Readiness Levels [164].

From here all the other major obstacles to new materials and processes application are visible. Immediately, time, costs and worker's experience, in addition to aeronautical regulation, stand out as some of the major obstacles being all of them linked somehow. As mentioned, and as seen from Figure 5.2, implementation of new technologies should be done for high readiness levels. New technologies with already great maturity, in what aeronautical manufacturing is concerned, will prevent the further costly delays in achieving component validation through FAI. To note that even a more traditional technology can cause delays due to errors in design and one should not see new technologies as the only source of problems. In addition to the increased time-to-validation, and consequently time-to-market and customer, of components using new technologies, one must also take into account the effects of applying new technologies in the learning curve related to workers' experience gain and their ability to become accustomed to the new technology. Aircraft production is characterized by strong learning effects, such that in the long term materials and labor initially required to produce an aircraft, decline some percentage [197]. Also, new technologies might require complex new skills, which if time-consuming or costly to acquire, will result in slower technology adoption [198].

In the end it all comes down to costs. If we take a look at the cost breakdown of an aircraft (Figure 5.3) we conclude that the choices made in materials and processes, during design, have influence in around 80% of the aircraft's total cost of ownership [199]. These costs include both recurring and non-recurring costs plus the costs of maintenance and of fuel consumption during the operational phase of an aircraft (other operational costs are excluded from this discussion, such as salaries, airport utilization, insurance, financial costs). Recurring costs are the unit costs arising from the manufacturing of the aircraft (labor and materials) and the production support, while the non-recurring costs are the one time only costs arising from engineering/design, tooling and prototyping and testing and certification including manufacturing of aircraft for flight testing [200]. Other additional non-recurring costs exist downstream the aircraft life cycle, namely costs arising from modifications. However, for the sake of simplicity only the design phase related non-recurring costs will be taken into account.

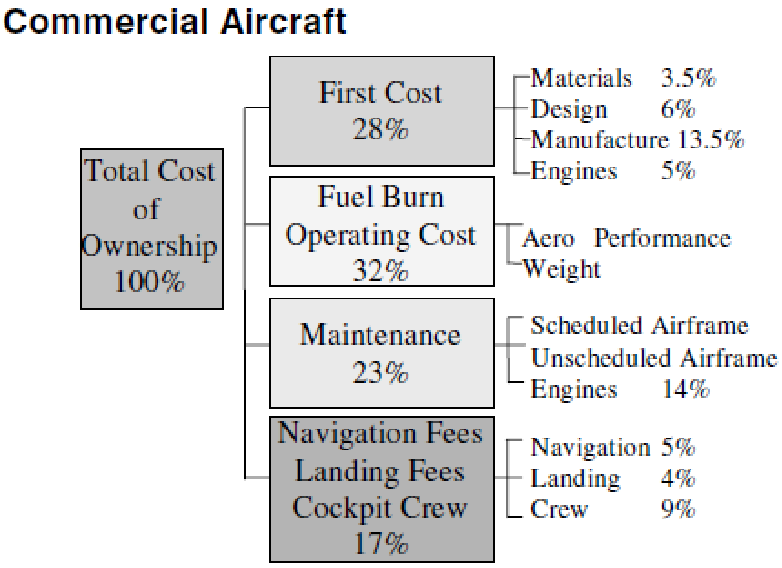


Figure 5.3 – Cost breakdown of a commercial aircraft [199].

Despite the difference between recurring and non-recurring costs, the choices during the design phase affect both. During the design process and once the configuration and systems are frozen we then enter the detailed phase and material and the process must be chosen for all components. The function assigned to the component dictates both the shape of the component and the material to be used. These will then determine the process to be used [201]. It is then obvious, from what was presented above, that the choices made for the materials and processes will directly affect recurring and non-recurring costs. These choices will also have repercussions on the operational phase of the aircraft. Materials choice will influence fuel consumption, by the influence they have on weight, and maintenance, as for example composite materials require more complex and specific maintenance techniques.

So, when it comes to the introduction of a new technology, manufacturers must take into account all these interdependences and their effect on what the price of the aircraft will be. Not only the acquisition price (Equation 1, where number of aircraft is the desired amount of aircraft necessary to be sold in order to amortize the non-recurring costs. This number is chosen by the manufacturer depending on the expected and confirmed orders for a certain aircraft [202]) but also the costs associated with the mentioned aspects of their operation. Furthermore, non-recurring costs will be affected by the costs of developing or acquiring those technologies, the costs arising from training employees, the costs associated with updating other complementary machinery and the costs associated with the installation of these new technologies, which can force production to a halt if machines' replacement is needed [198]. One can, then, conclude that the choice to adopt new technologies is not an easy one to make, especially on the aeronautical industry, because it introduces additional elements of risk and costs that could jeopardize the plans of delivery and/or the budget associated with the development of an aircraft. This is why manufacturers are very cautious to apply very revolutionary solutions and the aircraft has become a stagnant product in terms of innovation.

$$Price = \frac{Non-recurring\ costs}{Number\ of\ aircraft} + Recurring\ costs + Profit\ margin \qquad \text{(Eq. 1) [202]}$$

Classical product evolution pattern can be divided in three: fluid phase, transition phase and specific phase. Nowadays the aircraft, as a product, is deeply in the specific phase, in what product evolution is concerned, and much attention is given to its improvement in efficiency and in terms of production, rather than in product itself. In the specific phase a very specific product is produced with a high level of efficiency and product innovation shifts from product to process technologies, in other words, to design, development and manufacturing innovation. Changes in the product itself are scarce or not very significant [203]. This is true for the aircraft as, since the 70's, the aircraft's shape has not changed significantly and innovation is concentrated in the existing technologies. Nonetheless, opportunities for innovation are possible towards improved product performance and productivity, process technology and product substitutes [192, 203]. The desire to move forward in these terms exists and the actual change is therefore a trade-off choice, between investment and the expected gains to be obtained with the change, to be made by companies, based on the mixture of all factors here presented. Summarizing, the component specifications and function, controlled by aeronautical regulations to ensure safety and compliance with even environmental rules, will dictate the materials and processes that can be used [204]. After that, organizational decisions take place in assessing the advantages of adopting new materials and/or processes to ensure improved product properties in contrast to the costs associated with the new technology and their impact on what is the price of the aircraft.

Nowadays the principle of design for manufacture and assembly (DFMA), realizing the importance of the decisions made at the design stage in downstream life cycle phases, has been used for many years. This principle applied through integrated digital tools (CAD/CAM/CAE/CIM) that manage all information regarding materials, part fabrication, assembly, quality and industrial engineering allows an integrated cost framework for easier design and production management which will ultimately reduce time of design and will optimize costs for the entire life cycle of the aircraft. Other downstream life cycle phases such as test and certification, maintenance and operation, and disposal can be integrated using the mentioned digital tools in a way that they can be taken into account during the design stage [205].

6. Trends for future development of airframe manufacturing

With the current state of airframe construction presented, one can now look at the future prospects of its development. For that, it is first necessary to assess how the industry is expected to grow and assess the already identified trends for the future development of the aircraft, made by companies and academics. At the same time, goals have been set by international entities namely by the ACARE initiative, which sets quite ambitious goals for the European aeronautical research, to boost the industry's competitiveness in the years to come. Manufacturing technologies will, obviously, take a major role in achieving these goals and in the development of the aircraft in general, as a final product.

Being focused on the aircraft's airframe, the already presented manufacturing technologies related to composite materials and lightweight metal alloys, and the way they are introduced in the aeronautical industry, will serve as the basis for the conclusions of this work. So, what is intended in this chapter is to look at the goals and trends identified by the various aeronautical stakeholders and explore how they can be met from the airframe's manufacturing technologies point of view. Here, one must take into account all that has been presented so far. Not only the developments that are being undertaken in terms of composite materials and lightweight metal alloys, but also the restrictions arising from the introduction of new technologies in the aeronautical industry. This way a more credible trend for the future development of the airframe's manufacturing technologies and production can be proposed.

6.1. Industry forecast

As seen on Chapter 3, air transport has been growing steadily ever since it started to thrive right after the First World War. According to Airbus' latest long term forecast, from 2012 to 2031, and having in consideration the segment of aircraft above 100 seats and above 10tons for freight, air transport of passengers is expected to grow at a rate of 4,7% a year for the next 20 years, thus continuing the tendency that passenger traffic has of doubling every 15 years (Figure 6.1). In addition and at the same time, freight traffic is expected to grow at 4,9% a year for the same period of time. To accommodate this growth, also fleet size will have to grow. The same forecast by Airbus estimates a 3,8% yearly rate of passenger fleet increase. From the early 2012 fleet of around 15500 aircraft to the expected fleet in 2031 of 32500 aircraft, a demand worth some 2,8 trillion€ corresponding to 27300 new aircraft is necessary, of which 38% will be respective to current fleet replacements and the remaining 68% will be growth [206].

In a wider view, considering the same time period and the segment above 30 seats, Boeing also expects passenger air transport and freight to increase, in this case at a rate of 5% and 5,2% per year respectively. Passenger fleet size, according to Boeing, will also increase being expected a demand, worth 3,4 trillion€, for 34000 new aircraft, of which 41% will be aircraft to replace current ones and the remaining 59% will be fleet growth [207]. In terms of freight fleet, figures expected by both companies are quite similar with both Airbus and Boeing expecting a need of around 2700 aircraft, of which around 1800 will be converted from their passenger version and the remaining 900 will be new aircraft [206, 207].

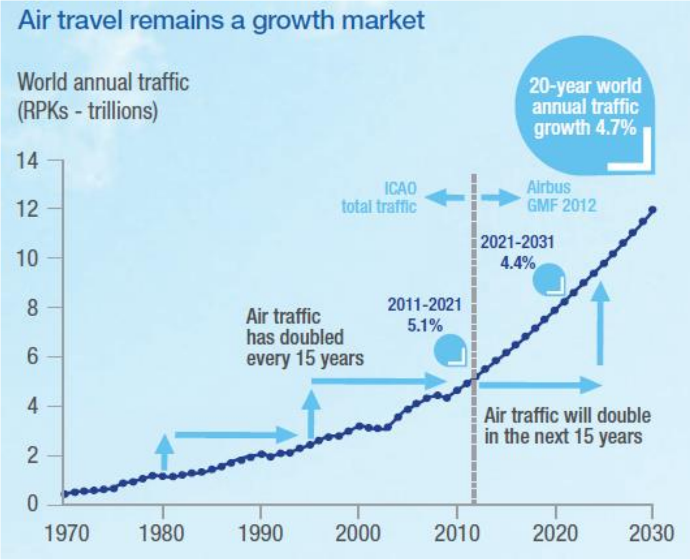


Figure 6.1 – Passenger air traffic growth since 1970 [206].

The increase in demand for air transport has made several airlines to enter the market, making it increasingly competitive. So, airlines searching for lower costs have «forced» this competition over to the manufacturers, demanding aircraft that not only provide operational cost reduction but also deliver the right seat capacity that airlines need, to explore routes more efficiently. However, designing a new aircraft is a long process that takes several years to accomplish, thus resulting in high costs that have to be amortized with sales. These high costs, transferred to customers, mean that introducing a new aircraft to the fleet is a costly matter. If considering the replacement of older generation aircraft with new generation ones, the new aircraft have to deliver substantial improvements over the previous generation, especially in terms of operating costs, so that it can be competitive for customers to perform the change. To be seen as competitive the new generation aircraft must provide a two digit improvement in operating cost reduction over the previous generation ones [208]. So, each new generation of commercial aircraft is designed using the latest technology so that the aircraft can have a longer life-cycle, typically around 20-25 years, and provide the mentioned improvement. Nowadays, the widebody segment is set for another generation with the introduction of A350 and B787 for the intermediate segment and A380 and B747-8 for the very large segment, while the single aisle segment is expected to enter a new generation no sooner than 2020, as the available technologies do not allow the improvement in efficiency that customers demand, needing further developments [208]. To boost these technological developments and to boost the competitiveness of the European aeronautical industry, the European Commission has created the ACARE initiative, establishing goals for the industry in general and for the aircraft in particular.

6.2. ACARE's goals

In 2011 the European Commission, through the ACARE initiative, has established a set of goals to improve European competitiveness in the various areas in the field of aeronautics for the next 40 years: the «Flightpath 2050» report. This document appears as an update to the 2001 report: «European Aeronautics: A Vision for 2020», which at the time already set some important goals not only in terms of quality and affordability of air transport but also in terms of flight safety and of industry's environmental sustainability [209, 210].

Throughout these reports the European Commission acknowledges the importance of aeronautics as a highly skilled job creating industry and as an industry capable of generating high revenues and exports. Although the reports mention goals to boost efficiency in air transport and in security and safety associated with aviation, for the purpose of this work, only the goals related with aircraft development and production will be outlined.

The «European Aeronautics: A Vision for 2020» report sets global leadership in the marketplace as the main goal for the European aeronautical industry. After that, the other major goals are: steady and continuous fall in travel charges through substantial cuts in operating costs, 50% reduction in noise, 50% reduction in CO_2 (which means a reduction of 50% in fuel consumption) per passenger kilometer and 80% reduction in NO_x, halve time-to-market for new products, increase collaboration between companies, universities and research institutes and make Europe the most competitive research system in the world [209].

On the «Flightpath 2050» report, however acknowledging Europe's current global leadership of the aeronautical industry, the European commission also acknowledges the fact that the increase in air transport and the entry in the market of new strong competition, in addition to the existing one, means increased challenges but also increased opportunities. So, and in order to maintain Europe's leadership in the industry for the decades to come, a set of goals were established. The report challenges the aeronautical industry to deliver the best products and services worldwide maintaining the leadership with more than 40% market share, to maintain leading edge in terms of design, manufacturing and systems integration as well as maintaining jobs, which should be supported by high profile projects, and to decrease development costs, including a 50% reduction in the cost of certification. At a more technical level, and acknowledging the importance of a greener industry, the report also sets a 75%

reduction in CO_2 emissions per passenger kilometer, a 90% reduction in NO_x emissions and a reduction of 65% in noise emission, all in comparison with a typical new aircraft from 2000. The aircraft must be emission-free when taxiing and be designed and manufactured to be recyclable. In addition, aviation must rely increasingly in more sustainable alternative fuels. Finally, Europe must remain a crucial player in what research, innovation, simulation and testing is concerned, by promoting collaboration between public and private stakeholders and between industry, universities and research institutes [210].

Looking at all these goals, one can realize the enormous challenges facing the European aeronautical industry, at the same time that, some hints regarding the necessary developments to meet these goals can already be identified for the industry in general and the aircraft in particular. To promote the actual accomplishment of ACARE's goals, the European Commission has created the Cleansky Joint Technology Initiative so that, through public-private partnership and investment, technological breakthrough developments and their application in the industry can be sped up and time-to-market shorten [211].

Being halfway to the first goals' deadline, the year 2020, one can already perceive some significant changes in the aircraft developed and brought to the market in the last decade. For example, since the launching of the first report in 2001, aircraft emissions have, in fact, been decreasing at a steady rate. In terms of CO_2 emissions, of which the aviation is responsible for 2% of all man-made emissions, a reduction of around 15% has been achieved with the new generation of engines (Figure 6.2), which contributed to improved overall fuel efficiency, according to IATA, of 16% between 2001 and 2008, thus resulting in a decrease in CO_2 emissions [212]. To note that ACARE predicts that in order to achieve the 50% reduction in CO_2 emissions, an increase of 20-25% in aircraft efficiency, of 15-20% in engine efficiency and 5-10% in air traffic management is necessary [213]. Moreover, the historical trends for both noise and pollutant emissions favors a decrease in both, with noise diminishing 50dB for the jet engine, since it was first applied to commercial aviation, nearly 70% reduction in CO_2 emissions, since the 60's, and around 40% reduction in NO_x, since the 70's [214]. Nevertheless, further developments are necessary for the accomplishment of the goals set.

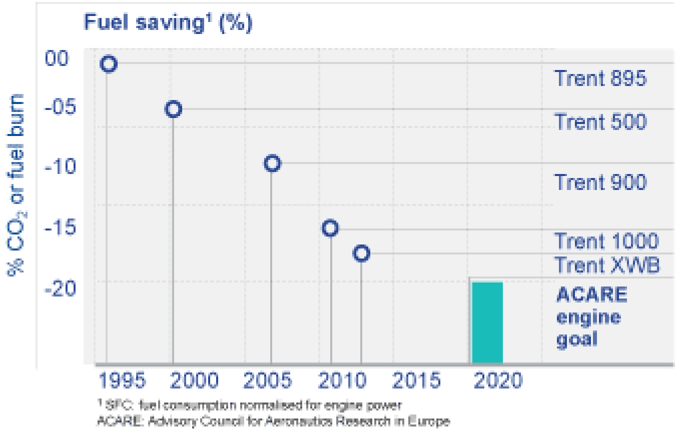


Figure 6.2 – Evolution of aircraft engines in terms of fuel savings/CO_2 reduction [215].

To achieve the mentioned goals developments will have to be done on the entire aircraft. For the purpose of this work, only the trends for the airframe development will be presented. Nevertheless, it is worth mentioning that to achieve ACARE's goals, the propulsive systems will also have an important role to play. In addition to the trends for airframe development, it is also necessary to consider the trends in aircraft design and production, as changes in these phases have a substantial importance in other downstream life-cycle phases as already discussed Chapter 5, and because aircraft production will have to cope with an increasing demand for aircraft. A wide variety of possibilities can be found in the literature, of which a brief summary will be presented.

6.3. Trends of development in the airframe

Many specific trends, namely for materials and manufacturing processes, have already been presented throughout Chapter 4, and so, during this section more general trends for the airframe will be presented, comprising structures, materials and aerodynamics. In terms of materials, the present trends tend to be the dominant ones for the years to come, as the necessity to reduce fuel consumption requires lighter aircraft and so weight reduction is essential. Composite materials and lightweight metal alloys will continue to replace heavier materials. Included are also hybrid alloys with a feasible potential of reducing weight by 10%. In what metals is concerned, it has been seen that titanium has revealed to be a good candidate to replace aluminum and especially steel in some more demanding applications at the same time that weight is kept low or even reduced. In addition, the new aluminum and magnesium alloys will still rival composite materials in the sense that producing components with these lightweight metals can result in a better overall mixture of important design parameters such as production costs and mechanical properties [216]. For example, a study conducted at the University of Delft has proven that for some components composite materials can be the worst choice, actually increasing weight rather than reducing it when compared to the use of aluminum [217].

However, weight reduction can be achieved by other means, other than by the use of lighter materials. During manufacturing, new techniques for joining, such as friction stir welding, can be used to reduce the amount of rivets or to replace conventional welding that adds material, in order to reduce weight. At the same time, systems to reduce moisture from the cabin crown and sidewall insulation can save up to half a ton of weight [216].

Other ways of improving fuel consumption, is through aerodynamic developments. By reducing drag, fuel consumption drops. In order to achieve this, laminar flow must be maintained and new surface finish and shaping techniques have been developed for future generation aircraft [218]. The maintenance of the laminar regime can result in a reduction of fuel consumption up to 15%. Also adding winglets provides improved aerodynamics, thus reducing fuel consumption [212]. In the end, aerodynamic trends can be summarized in maintaining laminar flow, decrease drag with turbulent flow and increase the aerodynamic efficiency of the wings [216]. Some of these technologies can actually be employed in already in-service aircraft just by modifying them, and so the trends presented can result in the continuous improvement of the aircraft.

Trends for the future development of the airframe also include less conventional concepts such as the wing-body configuration that could provide a reduction of 10% in fuel consumption just by adopting this new configuration, and morphing configurations, that would allow the aircraft to adapt to the flight conditions, thus optimizing performance [216].

In addition to morphing, other «smart structures» have been investigated as to allow, for example, the continuous monitoring of component's condition or self-healing structures. For these, new materials play a vital role, especially those known as multifunctional materials, which include nanomaterials and provide a wider range of properties to structures or other materials that otherwise would not have them [218, 219]. For example, the inclusion of nanotubes in composite materials, as already presented, can provide composite components with electric conductivity.

As mentioned, composite materials are expected to continue to substitute, to some extent, lightweight metals in the years to come in an effort to reduce weight and achieve the goals set in terms of fuel savings and consequently achieve low pollutant emissions, however, no attempt of quantifying this substitution in aircraft has been proposed, at least as far as the author is aware. So, a study was conducted to provide academics and stakeholders with an idea of the future diffusion of composite materials in aircraft construction and also how the mix of materials in an aircraft is expected to change. During the next section a forecast of the evolution in the mix of materials in aircraft construction is presented.

6.3.1. Forecast of the use of composite materials in aircraft construction

The diffusion or transfer of any technology can be described by an S-shaped curve known as logistic distribution [220]. These curves vary between 0 and an asymptotic value known as the saturation value, and can be divided in three regions. In the beginning, a slow growth is experienced, being followed, after some time, by an exponential growth, before reaching a saturation phase in which technology implementation and development follows an asymptotic curve. In this case, a technology substitution, of lightweight metals by composite materials, in the aircraft construction can be seen as logistic distribution (S-shaped curve). A logistic distribution follows the following expression [220]:

$$K = \frac{k}{1+e^{-\alpha(t-Tm)}} \qquad \text{(Eq. 2) [220]}$$

Where, k is the asymptotic value, α is the growth coefficient, t is time in years and Tm is the inflection point of the curve [220].

To obtain this curve it is first necessary to define the parameter that will be used to quantify the implementation of composite materials. In this case, percentage of total empty weight is considered. However, the remaining values that appear in equation 2 are completely unknown at this point. So, the idea is to begin from a collection of data and fit a curve to that data, using software, and extrapolate from it. This study was conducted using the IIASA's LSM2 program which is a simple and free tool dedicated to estimate the parameters of technological growth and substitution of processes, and hence generate logistic distributions [221].

To obtain the collection of data, an assessment of the percentage of total manufacturer empty weight of production commercial aircraft, with more than 100 passengers, from Boeing, Airbus, McDonnell Douglas, and Bombardier's CSeries was made and a tendency curve created from these data (Figures 6.3 and 6.4), using the mentioned software to obtain the parameters and Excel to plot the graphics. All of the data collected, available in annex, is already published data found in articles and in official documents and presentations from the manufacturers.

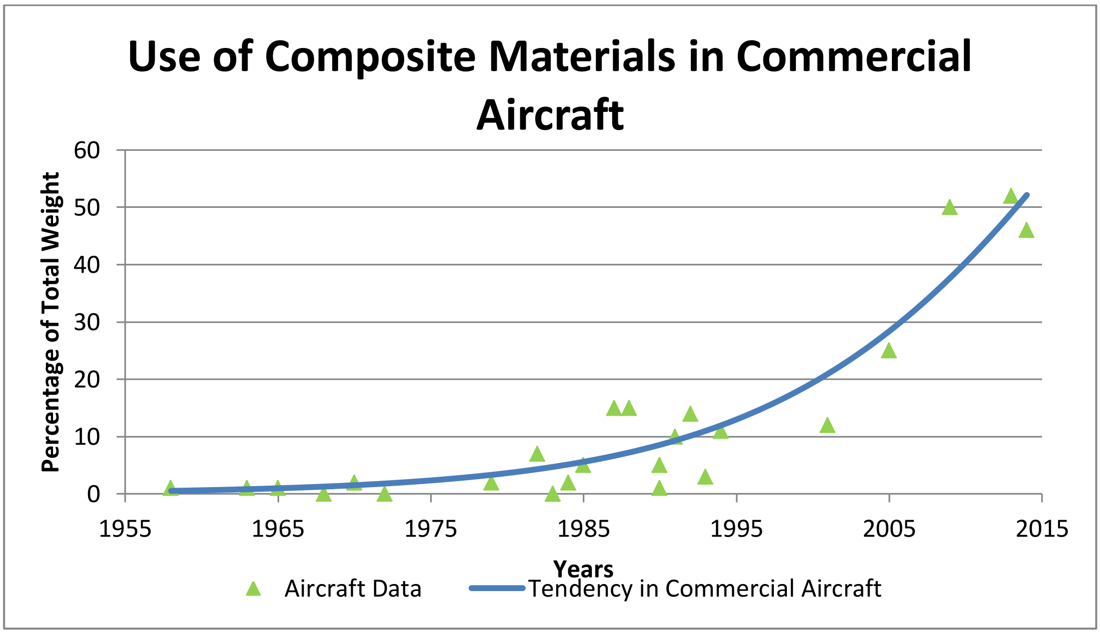


Figure 6.3 - Historical tendency of the use of composite materials in aircraft as percentage of total weight.

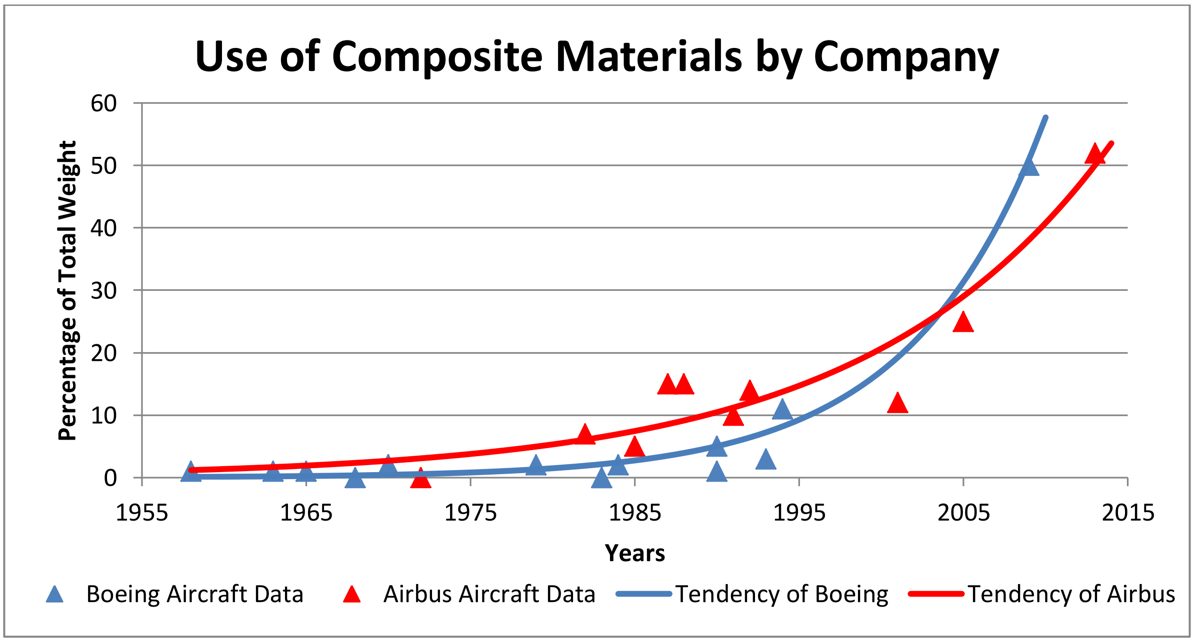


Figure 6.4 - Comparison between the historical tendencies of Boeing and Airbus. To note that McDonnell Douglas aircraft data are included in Boeing's.

From the figures presented, one can see that, in fact, the use of composite materials have experienced an exponential growth in the commercial sector of the aeronautical industry, and so, one can conclude that currently composite use is in its exponential phase of growth. Throughout the years, Boeing has been quite conservative as to use composite materials in a large scale, with the exception of the new generation 787, jumping from some 11% of total weight in the 777 to around 50% in the 787. To note that there is a 15 year gap between the two aircraft. The reasons for this jump have to do with technology maturation that was achieved in Boeing during the Sonic Cruiser program and with certain conclusions that arose from the internal ACPS initiative to produce an aircraft in half the time and half the cost. On the contrary, Airbus has, throughout the years, applied composite materials to its aircraft in an increasing manner, thus resulting in a less steep tendency curve. To note that in each new generation of aircraft, Airbus has used composite materials more extensively than Boeing.

With the historical trend, one can now extrapolate towards the future to see when the technology will saturate, in other words, when composite materials will reach their maximum application. Logistic distributions, as mentioned, vary from 0 to a saturation value, the k value. LSM2 does not recognize percentage and so results for the data used in this study are absurd with a k of 163 percent of total weight in composite materials, value that is reached in the year 2080. Even if percentage was acknowledged by the program, an entire aircraft made 100% of composite materials is unthinkable and unpractical, and so, one must impose some restraints to the extrapolation to build an S-shaped curve adherent with reality, in this case, impose a k value for the saturation. The approach taken was to find a range of maximum values for the percentage of total empty weight of an aircraft that could be attributed to composite materials.

To do this, one must look at the weight breakdown of an aircraft and see where composite materials can be applied. Figure 6.5 presents recent typical weight breakdown values for narrow body (single-aisle) and long range (double-aisle) aircraft.

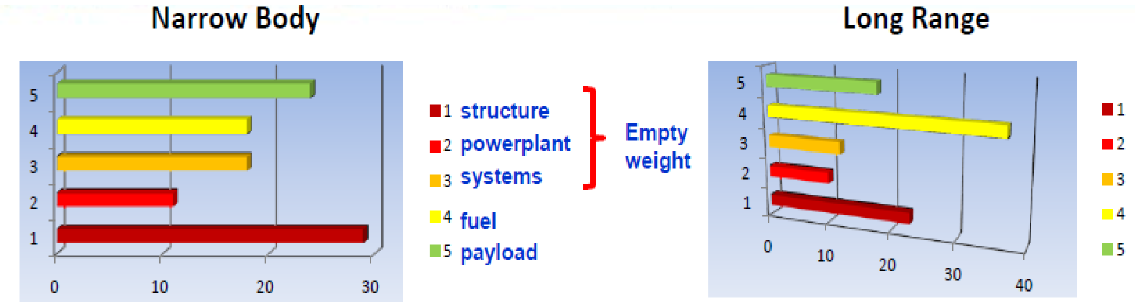


Figure 6.5 – Weight breakdown of a typical narrow body and long range aircraft [222].

From the figure, and considering only the empty weight, a percentage of 49% for the structure, 20% for the powerplant and 31% for the systems of the total empty weight was considered for the narrow body aircraft, while 52% for the structure, 20% for the powerplant and 28% for the systems of the total empty weight was considered for the long range aircraft. To note that, by structure is meant the weight of fuselage, wing, landing gear, empennage and control surfaces, and by systems is meant all the systems not included in the other categories such as the electric and pneumatic systems of the aircraft. A further breakdown of the weight of the structure can be made, as it is the main purpose of this work, and consequently for the fuselage and wing, being presented in Table 6.1.

Structure	% Total Weight NB	% Total Weight LR
Fuselage	21	22
Wing	16	17
Landing Gear	3	3
Empennage	6	7
Movable Parts	3	3

Fuselage	% Total Weight NB	% Total Weight LR
Skins	8	9
Stringers	5	5
Frames	4	4
Floor&Other	3	3

Wing	% Total Weight NB	% Total Weight LR
Skins	7	8
Stringers	5	5
Spars	1	1
Ribs	2	3

Table 6.1 – Further breakdown of the weight of the structure as percentage of total empty weight of the aircraft [222]. NB – Narrowbody LR – Long Range

Despite being credible values, as the source is a document from the Cleansky initiative, further confirmation of these values was performed, as some doubts arose from the fact that data from old aircraft, that is being used, would be different from current aircraft. To corroborate these values, the weight breakdown of some aircraft, spanning from the 70's to the newer ones, was found and the conversion of those data to percentage of total empty weight compared with the values presented are quite similar. Even when looking at the theoretical coefficients used in design to estimate the aircraft's weight (found in [223]), both the values found in [222] and the values obtained from the data hold true. From this comparison a conclusion was drawn that there is not a substantial difference in the weight breakdown of an older aircraft (mostly metallic construction) towards a new one (mostly composite construction), with the values varying as much as 5% and 10% for very large aircraft, namely the A380 and B747, and so, the values found in [222] were confirmed and used as a basis for the following work.

Current generation of aircraft, which have already 50% of their total weight in composite, have the entire fuselage, the skins of the wings and tail, and the nacelle of the engine in composite materials in addition to some components accounted as systems such as cabin interiors and cockpit dashboards. If these components account for 50% of the total aircraft empty weight, one can easily foresee that the maximum percentage of total empty weight in which composite materials can be used is between 60%, for a more reasonable prediction, and 70% for an ultimate maximum, taking into account possible breakthroughs in the development and application of composite materials.

Nowadays aircraft room exist for the further employment of composite materials in the powerplant, such as pylon skins and fan blades (in this case not likely polymeric composites), in the systems, by further applying composites to the interior of the cabin for example, and of course in the structure, especially in the internal structure of wings, fuselage and empennage.

These are the values for k that will be considered as 100%, in other words, two scenarios will be considered, one for 60% and another for 70%, in which these values are the maximum values for the use of composite materials in aircraft construction as percentage of total empty weight. These values were somewhat confirmed by analyzing the mix of materials used in aeronautics until now, namely aluminum, titanium and off course composite materials, as well as steel and other less significant materials, like magnesium and superalloys. Data for these materials was found for some aircraft (also in annex) and by using the LSM2 program a tendency of the substitution between the mentioned materials was performed and the result was as follows:

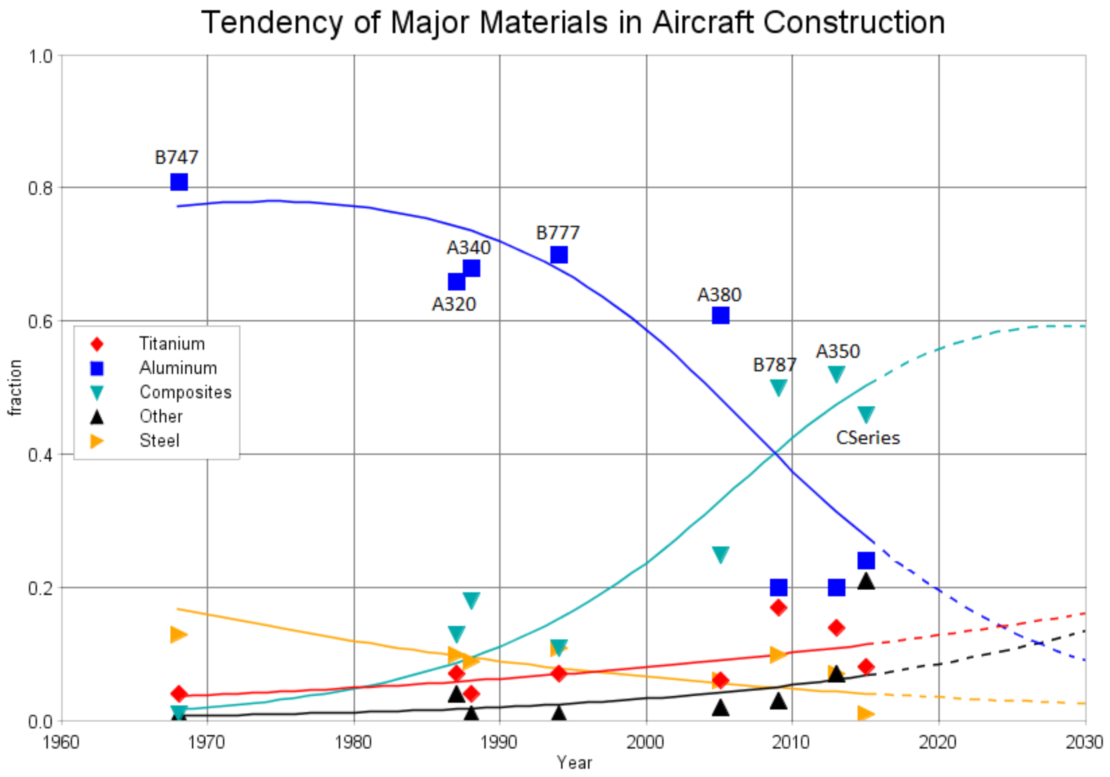


Figure 6.6 – Tendency of the mix of materials used in aircraft construction.

From figure 6.6 one can extract important conclusions, as follows:

First of all, composite materials are expected to reach a maximum of 60% of total aircraft weight, as assumed previously, by the year 2030. Then, and as said, the 70% value appears as an ultimate value admitting that in this time span technology breakthroughs will occur that allow this value. So, it must be seen as a hypothetic scenario.

Evidently, the main tendency that can be observed is the replacement of aluminum by composite materials. Nevertheless, the decrease of aluminum can also be explained by the increase of other materials, in particular magnesium alloys that, as was seen in Chapter 4 by the time an assessment of the state-of-the-art of lightweight metal alloys was made, are already quite competitive in comparison with aluminum ones, being corrosion resistant and, most importantly, lighter. Aside from magnesium, superalloys are also included in «others» and are expected to be replaced by titanium to some extent in the engine as was seen in Chapter 4 due to appearance of new titanium alloys less reactive at high temperatures and lighter than superalloys.

In addition, because new titanium alloys are stronger and lighter than steel, a trade-off between these materials is expected to exist, namely with titanium gaining terrain in some structural components.

Summarizing these tendencies, aluminum is expected to continue be replaced by composite materials and magnesium, while titanium will replace steel and superalloys.

So, one can conclude that the main driver for development, acknowledged nowadays, is the weight reduction, will in fact be the main driver for change in aircraft construction for the years to come. To note that, in general, the materials that will experience growth are also somewhat expensive to produce and manufacture, and so, customer operating cost reduction is expected to prevail over cost of acquisition as a driver of development. Nevertheless, cost reduction in production will continue to be a focus of attention by companies in order to gain that competitive advantage.

Now that the values for k have been «selected», a logistic distribution for composite materials can be drawn using LSM2. Inputting aircraft data, year of the model and percentage of total weight in composite, and the values for k, the results obtained were as follows:

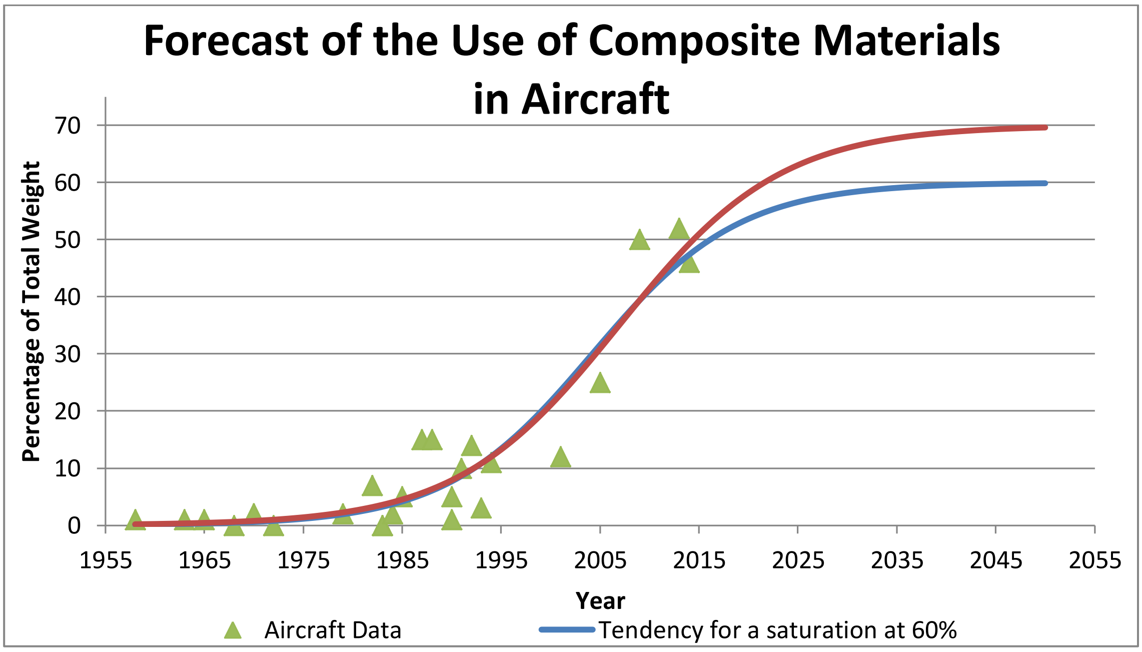


Figure 6.7 - Fitting for the data collected and extrapolation towards the saturation values k.

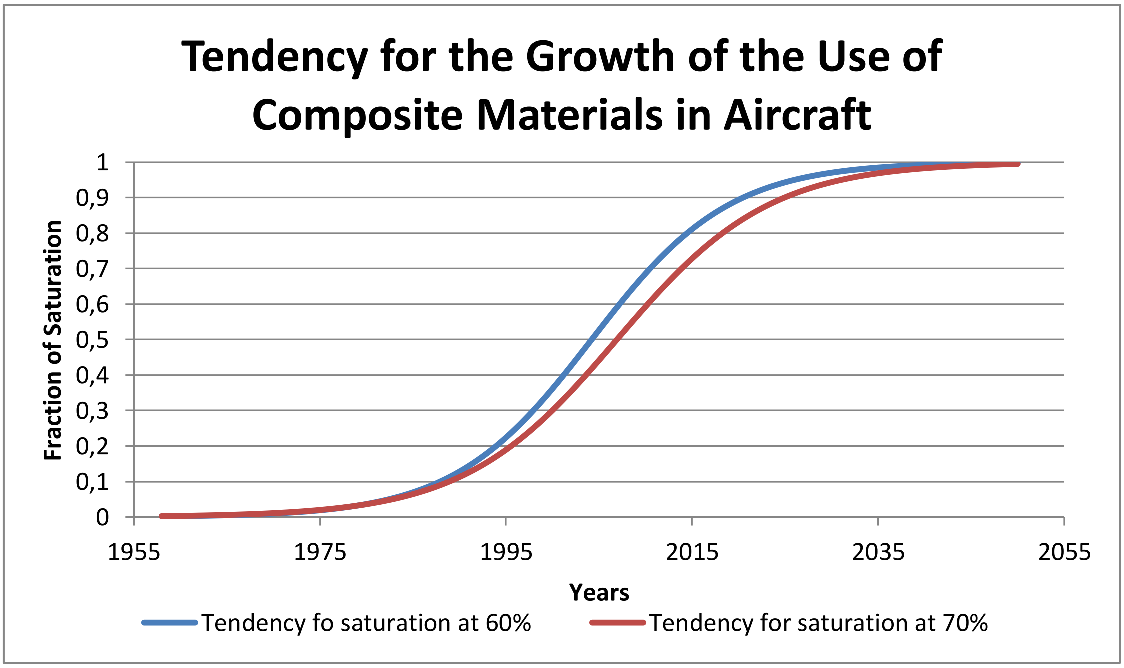


Figure 6.8 - Logistic distribution considering the saturation values k as 100%.

From the observation of the figures above, the tendency already identified previously is confirmed. To note that the values for k are asymptotic and so, the curves will not reach the value k. For the case of k=60%, the stagnation values are reached around 2035 while for k=70% are reached a few years later. For the type of distributions of figure 6.8, the more interesting values are those for 90% of the total value. In this case, 90% of the maximum value is first reached for 60% curve, as it would be expected, with a difference of around 4 years.

To debate if the results above are adherent with reality, one must consider the next generation aircraft and their predictable market entry. The next aircraft to enter the market will very likely be in the narrow-body segment, as the long range segment is set for another generation. Although the aircraft are similar in shape, a main important difference exists, that influence the choice of materials, between a long range aircraft and a narrow-body one. A narrow-body aircraft fly shorter distances and consequently perform many more take-offs, landings and pressurization cycles each day than the long range aircraft.

This requires a more robust airframe to withstand the stresses arising from this increased number of cycles [224]. To cope with this fact metals are obviously the first choice, or it seems that way. However, taking a look at the CSeries, which is a narrow-body aircraft similar to the A320 and B737 that will enter the market by 2015, one can see that the amount of composite materials as percentage of total empty weight is very close to that of the new long range aircraft with 46% [225].

Even considering the A400M, a military transport aircraft that must endure hard operation, composite materials have been used quite extensively, reaching 36% of total empty weight. Both the A400M and the CSeries cases show the confidence companies already attribute to composite materials.

In conclusion, composite materials can in fact reach very high percentage of total empty weight by the time Boeing and Airbus release their new narrow-body aircraft as this study suggests. However, it must be noted that, in this study, parameters are fixed rather than variable and so, technological breakthroughs, such as revolutionary fibers or resins, or less benefic events, such as an eventual failure of recent models to succeed in the world market or the an improved competition from metals, can speed up or slow down and increase or limit the maximum value for the growth of the use of composite materials in aircraft construction. In other words this study should be seen as a very likely scenario that can change due to extraordinary circumstances or events.

6.4. Trends of development in design and production

Development and production costs are relevant parameters that can greatly influence the customer's decision to acquire an aircraft, being accounted as costs of acquisition. Recalling the cost of ownership breakdown presented in Figure 5.3 from Chapter 5, one can see that the cost of acquisition can account to up to 28% of the total cost of ownership. Acknowledging this fact, and the importance that the reduction of these costs have in companies' competitiveness, the European Commission through the ACARE initiative has included the reduction of these costs in the roll of goals proposed for both 2020 and 2050, as presented above. During Chapter 3, the current model for aircraft production was assessed and some trends were outlined. In addition, trends for developments in production were outlined during the assessment made for manufacturing processes for both composite materials and lightweight metal alloys.

In order to provide a competitive product, nowadays the supply chain in the industry must face the prime drivers of cost, both of acquisition and of life cycle, time-to-market and performance. To achieve this, an integrated approach is essential, combining the choice of materials, manufacturing processes and design. Furthermore, this approach must be shared by the entire supply chain in order to minimize costs and maximize performance in the required timescale [199]. Currently, risk sharing techniques and collaboration between companies, what has been mentioned in the literature as «virtual networks», has been increasing for the newer generation of aircraft. These techniques and collaboration are expected to become even more common as ties between OEM's and suppliers become tighter. In the future tendencies are for further virtualization of these networks, resulting in greater manufacturing at a global scale, increased formation of strategic alliances between companies, in greater production flexibility and in increased mass customization [226].

At the production level, lean principles are expected to continue to be used at an increasing scale to reduce waste, at the same time that the continuous optimization of production is promoted. Referring to the assembly of the B787, Boeing has been capable of reducing time of assembly and the necessary space to do it just by reorganizing the various intervenient in assembly, in other words, parts, tools and people come to the precise point along the line where they are needed at the time they are needed [227]. However, the need for customization and the future need for huge numbers of new aircraft will continue to force manufacturers to adapt production faster and so more adaptive and flexible production systems will be the tendency for the future [228].

In terms of design, the need for an integrated approach will continue to make manufacturers rely on digital tools such as CAD and CAM in order to simplify and better organize design.

7. Conclusions

The purpose of this work was to assess the current state of manufacturing technologies for the airframe, and identify and propose the path through which developments on these technologies is foreseeable. After assessing the early development of these technologies, their current state and their already identified trends for future developments, conclusions can now be taken regarding what will be airframe manufacturing. Obviously, it is important to take into account how the introduction of new technologies in the aeronautical industry is made and what challenges does that represent for companies.

In this work attention was given to both composite materials and lightweight metal alloys as these kinds of materials are the predominant ones in an aircraft, and will continue to be. The percentage of the commercial aircraft's total empty weight in composite materials will increase up to 60%, in a more reasonable estimation, and up to 70% in a more optimistic estimation, at the expense of the reduction in lightweight metal alloys, namely aluminum. For this to happen, some of the disadvantages of composite materials will have to be vy the aircraft OEM. Recalling Chapter 5, the application of new technologies will always depend on the technology's maturity and on the trade-off between the costs arising from the development of such technology and the benefits that can be obtained with it. As seen on Chapter 6 the costs of production seem to be relegated to second plan, becoming customer value the main driver for the application of new materials. Nevertheless, companies, looking for more competitive products, will continue push production costs down.

So, and with this in mind, production costs will be reduced by using more efficient manufacturing processes, in terms of material usage and energy consumption for example, with as good or even better component's mechanical properties as the current processes. Out-of-autoclave processes, in particular resin infusion processes, will become widely used at the same time that process automation will replace even more current hand lay-up made components as the decrease in cost of these equipment will allow the increase in their use and their development will allow more complex shapes, better material usage and less component defects.

To further facilitate the use of composite materials in a wider range of components, inspection of composite components will become more accurate, economical and faster, thus allowing an easing of the process of certification of composite components at the same time that repairs will become more effective, not only because defects will be detected with more accuracy, but also because new methods, such as resin infiltration, will improve the quality of repairs. This will mean the reduction in the use of mechanical repairs, which increases weight. In addition, the increase in understanding the failure mechanisms of composite materials, the use of seaming to provide transversal resistance and the development of fibers and resins with improved properties, will, in the end, contribute for the improvement in quality and resistance of composite components, thus reducing the need for repair. Although still quite far in terms of aeronautical applications, nanocomposites will be the focus of much attention, in what investigation is concerned, in the years to come.

However, lightweight metal alloys will also continue to have an important role, especially in replacing heavier metals in more demanding structural applications. The new titanium alloys will replace in part steel and some superalloys in aircraft construction, due to its lower weight, lower high temperature reactivity and high strength. In the case of aluminum, its replacement by composite materials and even by the new magnesium alloys, that can provide basically the same mechanical properties at a lower weight, is expected to continue. However, the new aluminum-lithium alloys will make this replacement slower as they provide very competitive mechanical properties and weight reduction even when compared with composite materials. Both these materials will continue to be used in components where composite materials do not offer the best solution, whether in terms of weight or mechanical properties, and their future developments will also make the choice even harder for aircraft manufacturers.

Most developments, in what lightweight metal alloys is concerned, will occur in machining metals to the desired shape and in properties enhancement, via new alloys, new heat treatments and improved manufacturing processes. Manufacturing processes for lightweight metal alloys will become increasingly more efficient, reducing waste of material and energy costs, increasing component quality and improving material properties, due to the induction of strains during the material's deformation. Additive manufacturing will become widespread, as it allows the reduction of time required to make a component, the number of tools necessary and allows the production of components that need few or none machining.

Also, the superplastic properties of some alloys will continue to be exploited, as these alloys allow quite complex shaping and the easy forming of components. Again, nanomaterials in the field of lightweight metals will be a focus of much attention, especially with the purpose of applying nano layers that act as coatings to improve material's properties and protect them against, for example, corrosion. The repair of metals is not expected to change much from the current techniques. The use of adhesives in the form of patches will become increasingly used, also benefiting from the development of inspection technologies for composite materials.

In terms of joining, for both composite materials and lightweight metal alloys, mechanical fasteners will be increasingly replaced by adhesive bonds, which have various advantages, already discussed over the previous ones, such as not being necessary to drill the component in order to pass through the hole any rivet or bolt. Welding will also continue to play a vital role in aircraft construction. In metals the use of welding, mostly by friction and laser but also hybrid welding, will be widely used, as improvements in these processes will allow their application to an increased range of metals. Also for composite materials, welding will have increased application, namely for hybrid materials of composite-metal.

With new regulation regarding environmental sustainability, recycling will be a major concern and certain barriers will have to be overcome. In addition, with the majority of the aircraft's weight shifting from metal to composite materials, the recycling of these materials will gain a substantial importance. First, the dismantling of the aircraft and the sorting out of the resulting scrap will be more efficient, thus reducing the contamination of materials with others. In the case of composite materials, the implementation of a viable recycling industry conjugated with an increased effort towards the certification of recycled composite materials for less demanding applications will be the path to follow.

This «new» industry will be capable of providing recycled materials with lower loss of mechanical properties in both fibers and resins. To achieve this, process efficiency will have to be increased, fact that will also be true for the recycling of metals. As a consequence, these recycled materials will have an increasing importance in a wider range of industries, even in the aeronautical one. Recalling that it is believed that 90% of an aircraft can be somehow valorized after the aircraft's end-of-life cycle and that nowadays 60% is hardly valorized, the improvements in the recycling process will not only maintain the 60% of valorization, endangered by the replacement of metals with composite materials, but will eventually raise that figure. Towards the environmental sustainability of composite materials, biofibers and biodegradable resins will also be the focus of much investigation, being possible their use in less demanding applications.

Lastly, and looking at the way airframes will be designed and built, one can expect an even more global scale manufacturing network of N tier suppliers, with strong ties, in the form of risk sharing schemes, linking them to OEM's and their projects. In this sense, even the transfer of new technologies is expected to increase from OEM's to suppliers or vice-versa. Furthermore, the increase in demand for new aircraft in the upcoming years, will force manufacturers to rapidly adapt to new, more customized orders, and so, production flexibility will be an important factor of competitiveness.

With manufacturing reaching global scale, the flexibilization of production will face severe challenges, which will be surpassed by further integrating the various aspects of design and production into digital tools, thus facilitating the exchange of information and facilitating eventual changes to design. This more integrated approach to design will result in a better understanding of the consequences of the choices made during design in downstream life cycle phases. In the end, this approach will implicate a cost reduction for operators, not only in terms of the operation itself, but also in terms of disposal and acquisition, with production costs being diminished, for example, by a better organization of production and by the easiness of changing design.

Summarizing all that has been concluded:

- Composite materials will continue to replace lightweight metal alloys, namely aluminum ones with the exception of hybrid materials, reaching 60% of total empty weight possibly by the next generation of Airbus's and Boeing's narrow-body aircraft around 2025-2030, but certainly by the next generation of long range aircraft.

- Composite materials will benefit from less costly processes, namely out-of-autoclave processes, increased rate of production, new seaming patterns, improved inspection and joining methods and most importantly from a new recycling industry, contributing for a more environmentally sustainable aeronautical industry.

- Lightweight metal alloys will continue to have an important role in aircraft construction, benefiting from the existing knowledge in working with these materials, including disposal and repair, and from further developments in more precise and economical manufacturing processes, from shaping to machining ones.

- The importance of aluminum in aircraft construction will diminish while the importance of magnesium and titanium will rise.

- Aluminum-lithium alloys will be a strong competitor to composite materials especially in the narrow-body segment.

- Magnesium alloys, becoming increasingly competitive towards aluminum, will replace it in some applications.

- Titanium alloys will essentially replace steel in some important structural applications and the heavy superalloys in hotter parts of the engine.

- Weight reduction will continue to be the main driver in terms of materials application followed by increased customer value. Cost of production will not be as important as these two but will be pursued by companies in order to obtain competitive advantage.

- Production costs will be reduced, not only by improved manufacturing processes, but also by a better organization of production, increased cooperation with suppliers and by using a more integrated approach in design and production.

- Production will reach a more global scale, becoming more flexible and adaptable in order to respond to the predictable increase in demand for aircraft.

- The industry in general will become «greener» with an increasing percentage of the entire airplane becoming recyclable, while new biofuels and the reduction in fuel consumption arising from aerodynamic advances, decrease in weight of the aircraft, more efficient engines and better management of operation, will contribute to the reduction of pollutant emissions very likely in the order of that set on the ACARE’s goals.

8. Recommendations for future works

In future works the extension of the analysis to other parts of the aircraft, namely to the powerplant, and a more in-depth analysis of the impact of decisions during design in customer operations and also on production, by the presentation of case studies for example, is advised. Furthermore, the assessment of the state-of-the-art of the aspects, presented in this work, could be extended to other materials, namely superalloys and steel.

Advised also, is a more detailed collection of data that could be included in the study here presented for the trends in the mix of materials in aircraft construction, trying to narrow even further the category «others», possibly with the inclusion of superalloys.

Another approach to the gathering of information regarding the expected future trends in aircraft construction and development is via an inquiry to companies. This approach was tried with the European aeronautical industry during this work but with residual success, being received very little responses, hence its omission from the present document. In order to obtain a significant amount of answers, a more direct approach is advisable. To achieve this, meetings with company representatives during the many events that occur around Europe, such as Air Festivals, could be performed, media related with the sector should be contacted to assess if they possess any information regarding companies' opinions and students associations dedicated to the sector such as EUROAVIA and companies associations as for example ASD should be contacted as they possess closer ties with companies that could facilitate the response to the inquiry.

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Annex - Aircraft Data

Modelo	Year	Composites	Aluminum	Titanium	Steel	Other
Boeing 707	1958	1	-	-	-	-
Boeing 727	1963	1	-	1	-	-
McDonnel Douglas DC-9	1965	1	-	-	-	-
B737	1967	-	-	4	-	-
B747	1968	1	81	4	13	1
L-1011	1970	2	-	-	-	-
McDonnel Douglas DC-10	1970	2	-	-	-	-
A300-600	1972	4,5	-	3	-	-
MD-80	1979	2	-	-	-	-
A310-200	1982	7	-	-	-	-
B757	1983	2,5	-	4	-	-
B767	1983	2,5	-	2	-	-
B737-300	1984	2	-	-	-	-
A310-300	1985	5	-	-	-	-
A320-200	1987	13	66	7	10	4
A340	1987	18	68	4	9	1
A321	1988	15	-	-	-	-
B747-400	1990	1	-	-	-	-
McDonnel Douglas MD-11	1990	5	-	-	-	-
A340-300	1991	10	-	-	-	-
A330	1992	14	-	4	-	-
MD-90	1993	3	-	-	-	-
B777	1994	11	70	7	11	1
A340-600	2001	12	-	-	-	-
A380	2005	25	61	6	6	2
B787	2009	50	20	17	10	3
A350-900	2013	52	20	14	7	7
Bombardier Cseries	2014	46	24	8	1	21